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by

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ABSTRACT

An extensive and varied test program was carried out on four GRP rod and rope materials to evaluate tensile strengths, moduli of elasticity, flexibility at low temperatures, effects of simulated Aeolian vibration, and stress-rupture properties at moderate elevated temperatures both with and without high humidity. The effects of elevated temperature on long-term storage capabilities were investigated, and diameter-temperature relationships were established for avoiding buckling due to storage in a coiled condition.

The performances of five commercially available end fittings on these materials were examined in terms of the breaking loads attained in tensile tests. Using finite-element analyses, an improved end fitting was developed. With this end fitting the strength of the fitting-specimen system approaches the true tensile strength of the specimen for two of the GRP materials. An experimental stress analysis of the improved fitting was performed.

Key Words: Aeolian vibration, simulated; composite materials; end fittings for GRP rod and rope; grips, guy; guys, antenna; humidity, effects on GRP; mechanical properties of GRP; pultruded rod; reinforced plastics, rod and rope; rope, GRP; static fatigue of GRP.

1. INTRODUCTION

Glass-reinforced plastic (GRP) rod and rope products offer many advantages relative to comparable steel products. GRP rod and rope are strong, flexible, lightweight, non-conducting, corrosion resisting and

inexpensive. These products have been finding increased use in applications which had previously utilized other materials. For example, GRP rope has been used for tethering high-altitude balloons [1]* and for deep-sea mooring of oceanographic buoys [2]. GRP rod has been used as guy strain insulators [3], and both the rod [4] and the rope have been used, instead of steel, for entire guy lines and other elements of large communications towers and antenna arrays. The investigation described here pertains primarily to the latter application but many of the results obtained are relevant to the other applications as well.

The purpose of this study was to evaluate some of the structural properties of four commercially available GRP rod and rope materials. This evaluation included

1. measurements of density, tensile strength and tensile modulus of elasticity as a function of diameter,

2. determination of flexural moduli of elasticity at sub-zero temperatures,

3. study of the effects of Aeolian vibration on tensile breaking strength,

4. stress-rupture tests at moderate elevated temperatures both with and without high humidity conditions, and

5. investigation of buckling failures resulting from long-term storage in the coiled condition at moderate elevated temperatures.

In addition, the influence of several commercially available end fittings on the tensile breaking strengths of GRP rod and rope were examined, and a new end fitting was developed.

This investigation was carried out in the Engineering Mechanics Section of the National Bureau of Standards under the sponsorship and with the financial assistance of the Army Electronics Command, the Naval Facilities Engineering Command, Rome Air Development Center (USAF), the United States Information Agency, and NBS. The period of performance was April 15, 1970 through July 14, 1972.

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*Figures in brackets denote references cited on page 80.

In October, 1971 a new program was initiated at this laboratory, under the sponsorship of the Air Force Materials Laboratory, to develop an improved non-metallic antenna support material. A part of the financial assistance which was provided was earmarked for an expansion of the effort to develop improved end fittings for GRP rod and rope. That portion of this effort which was completed prior to July 15, 1972 is included in this report. This effort is continuing.

The U.S.A. is a signatory to the General Conference of Weights and Measures which gave official status to the metric SI system of units in 1960. However, for simplicity, only U.S. customary units have been used in this report. Conversion factors for these units are given in the Appendix.

2. ROD AND ROPE MATERIALS

Four, commercially available, GRP rod and rope materials were tested in this program. All are fabricated with unidirectional, continuous, glass fiber roving.

2.1 Material A

Material A is fabricated from S-glass and an epoxy resin matrix in the form of small-diameter rods or strands up to 0.119 in in diameter. The manufacturing process for this material has been patented [5]. According to the patent the individual fibers are 0.00036 in in diameter (Type G) and the resin is a conventional epoxy formulation (i.e., based on epichlorhydrin and bisphenol A) cured with boron trifluoride monoethylamine complex. However, the manufacturer states that the resin system actually used is different from that cited in the patent and was selected for greater moisture resistance.

Material A is also available in a rope-type configuration consisting of seven 0.119-in strands twisted together with a long helical pitch. Both hand- and machine-wrapped products are made.

2.2 Material E

Material E is a rod product which is fabricated, by the pultrusion process [3, 6, 7], from E-glass and a polyester resin matrix. Although 1/2-in diameter rod is available the manufacturer normally stocks only 13/16- and 1-in diameter products. The individual glass fibers are 0.00051 in in diameter (Type K). As a consequence of the manufacturing process an integral gel coating of the matrix material is formed on the outer surface of the rod.

2.3 Material G

Material G is a rope product fabricated from E-glass and an epoxy novolac resin matrix. The manufacturing process for this material has been patented [8, 9]. According to the patent, the glass rovings are impregnated with the resin, several such impregnated rovings are compacted together to form a single strand, each strand is lubricated with a silicone resin, then several strands are twisted together and cured. In this process the rope assumes a permanently twisted configuration although the lubricant permits the strands to slide relative to each other. The rope is coated with a polyurethane jacket, approximately 0.015 in thick. It is presently available in sizes from 1/8 to 1/2 in in diameter, which correspond to 1 x 7 and 7 x 19 configurations (no. of strands x rovings per strand), respectively.

2.4 Material N

Material N is a pultruded rod product fabricated from E-glass and a polyester resin matrix. It is normally available in sizes from 1/4 to 1-in in diameter. The individual glass fibers are 0.00051 in in diameter (Type K). The matrix resin system is reported by the manufacturer to be an "epoxy-modified" polyester. The rod is coated with epoxy that is heavily loaded with titanium dioxide for resistance to ultraviolet radiation. Thickness of the coating is 0.005 to 0.015 in.

3. EVALUATION OF COMMERCIAL END FITTINGS

Five types of commercially available end fittings for GRP rod and rope were evaluated. The evaluations were based entirely on tensile tests which were carried out in universal testing machines at room temperature and a relative humidity between 45 and 50 percent. One size of each of the four GRP materials was used, namely, Material A in the 7-strand configuration, 1/2-in Material E, 7/16-in Material G and 1/2-in Material N, but not every material was tested with every end fitting. Except where otherwise specified, a crosshead speed of 0.75 in/min was used.

3.1 Type P Fitting

The Type P fitting is a mechanical fitting of the dead-end type which, according to its manufacturer, is intended primarily for use on Material N rod. In this program the fitting was used on Material A rope and Material E rod in addition to Material N rod. The fitting, Figure 1, consists of a series of parallel, helically formed, galvanized steel strands which are wrapped around the end of the specimen. The end of

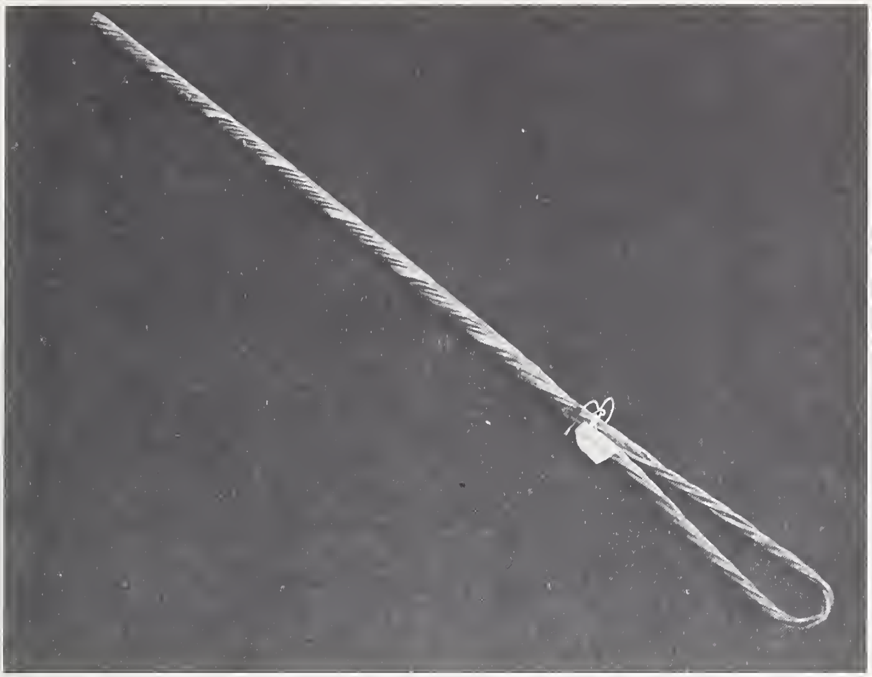


Figure 1 - Type P end fitting.

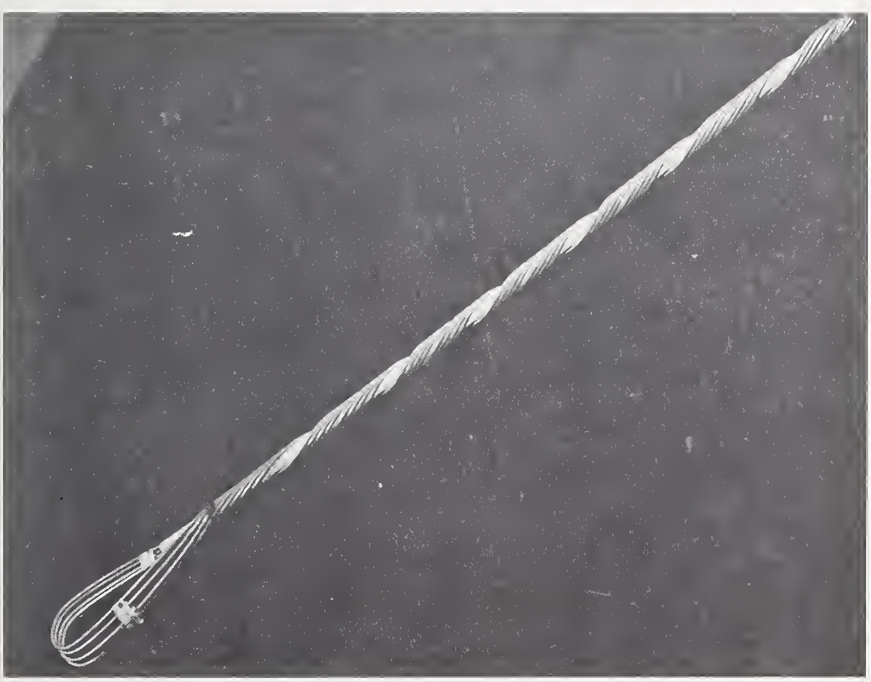


Figure 2 - Type F end fitting.

the fitting is formed into a loop for attachment to thimble-eye type hardware.

The fitting operates on the so-called "Chinese finger" principle; as tensile load is applied the strands tend to grip the specimen more tightly. The inner surfaces of the strands, where they contact the specimen, are coated with an abrasive material to provide additional gripping strength. Unfortunately, the strands also tend to twist, or unwind, under tensile load and this characteristic contributes to the failure of the specimen.

The test results are given in Table 1. Failure of the Materials E and N rods generally took place in the free lengths of the specimens but was triggered by longitudinal splitting which apparently initiated in the fitting. This splitting was quite obviously a shear phenomenon induced, in part, by the twisting of the rods by the fittings. Test No. 31004 was an exception; the Material E rod pulled out of the fitting prematurely and remained intact. The average maximum load for the other two tests of Material E was 26000 lbf.

Failure of the Material A rope took place at the end fitting with the individual strands of the rope breaking in rapid succession. (This mode of failure, which is discussed in several places in this report, will hereafter be denoted by the phrase, "strandwise at the fitting".) This failure also appeared to be induced, in part, by the twist imparted to the rope by the fittings. The natural helical twist in the rope material is small compared with the twist produced by the fittings.

The maximum loads obtained with Material A are in substantial agreement with those of previous tests conducted in this laboratory. In that work [10] three tests of 7-strand Material A with Type P fittings gave maximum loads between 17000 and 18000 lbf. On this basis it appears that the low strength value attained in Test No. 51065 is atypical.

The maximum loads obtained with Material N are also in good agreement with those obtained previously [10]. In that work four tests of 1/2-in Material N with Type P fittings gave breaking loads ranging from 19300 to 21500 lbf.

Since the failures in all of these tests were induced, to some extent, by the fittings it is felt that in no case was the true tensile strength of the specimen material approached.

3.2 Type F Fitting

The Type F fitting, Figure 2, is a mechanical fitting of the dead-end type which is very similar to the Type P fitting. According to its

Table 1 - Tension Tests with Type P Fittings

Test No.	Material	Gripped length[a]	Free length	Maximum load	Failure
		in	in	lbf	
51064	A, 7-strand	30	35	17,200	(b)
51065	A, 7-strand	31	36	13,000	(b)
51066	A, 7-strand	31	37	17,000	(b)
				15,700 average	
31004	E, 1/2-in dia	40	24	17,000	(c)
41037	E, 1/2-in dia	40	24	26,500	(d)
41038	E, 1/2-in dia	40	24	25,500	(d)
				23,000 average	
31003	N, 1/2-in dia	40	24	18,950	(d)
41041	N, 1/2-in dia	40	24	20,000	(d)
41042	N, 1/2-in dia	40	24	20,500	(d)
				19,800 average	

(a) Each end.

(b) Strandwise at the fitting.

(c) Pullout.

(d) Longitudinal splitting in the fitting.

manufacturer it, too, is intended primarily for Material N rod although it was also used on Material A rope and Material E rod in this investigation. The most obvious difference between the Type P and Type F fittings is in the loop. In the Type P fitting the strands in the loop are twisted together while in the Type F fitting they are not. Also, for a given specimen diameter the appropriate Type F fitting is somewhat shorter than the corresponding Type P fitting. The difference is small except in the larger sizes.

The test results are given in Table 2. Failure of the Material A rope took place in the same manner as it did with the Type P fittings, i.e., strandwise at the fitting. Similarly, failure of the Material N rod was in the same manner as with the Type P fittings, i.e., in the free length following longitudinal splitting. With the Material E rod, however, only one of the three specimens failed in this way; the other two pulled out of the fitting. In no case did it appear as though the true tensile strength of the specimen material had been approached.

3.3 Type F/A Fitting

The Type F/A fitting is a variation of the Type F fitting and is intended, according to its manufacturer, for use with Material G rope. See Figure 3. The fitting is in two parts, an armor jacket and a looped fitting, the latter being similar to a large-diameter Type F fitting. The jacket, which consists of helically formed steel wire strands, is first wrapped around the rope and then the looped fitting is installed over the jacket. The jacket and the looped fitting are wrapped in opposite directions to reduce twisting under tensile load.

The test results are given in Table 3. Each of the three tests resulted in a different mode of failure. In the first test one of the fittings failed, in the second test the rope specimen failed in its free length, and in the third test the rope specimen pulled out of one of the fittings. Because of the free length failure, it is believed that the true tensile strength of Material G was approached in these tests.

3.4 Type R/V Fitting

The Type R/V fitting is a basket-type mechanical end fitting for GRP rod materials. See Figure 4. It grips the rod with a spring-loaded jaw system contained within the conical basket. The jaws are, essentially, wedges of a segmented cone. The basket is fitted with a yoke and bail for attachment to thimble-eye type hardware. The basket and the yoke are aluminum alloy, the jaws and the bail are stainless steel.

Table 2 - Tension Tests with Type F Fittings

Test No.	Material	Gripped length[a]	Free length	Maximum load	Failure
		in	in	lbf	
51067	A, 7-strand	24	37	15,600	(b)
51068	A, 7-strand	24	24	15,300	(b)
				15,400 average	
31002	E, 1/2-in dia	34	24	26,000	(c)
41035	E, 1/2-in dia	34	24	26,000	(c)
41036	E, 1/2-in dia	34	24	26,500	(d)
				26,200 average	
31001	N, 1/2-in dia	34	24	19,700	(d)
41039	N, 1/2-in dia	34	24	19,000	(d)
41040	N, 1/2-in dia	34	24	19,500	(d)
				19,400 average	

(a) Each end.

(b) Strandwise at the fitting.

(c) Pullout

(d) Longitudinal splitting in the fitting.

Table 3 - Tension Tests with Type F/A Fittings

Test No.	Material	Gripped length[a]	Free length	Maximum load	Failure
		in	in	lbf	
41043	G, 7/16-in dia	34	24	22,000	(b)
41044	G, 7/16-in dia	34	24	22,000	(c)
41045	G, 7/16-in dia	34	24	21,700	(d)
				21,900 average	

(a) Each end.

(b) Failure of fitting.

(c) Failure in free length.

(d) Pullout.

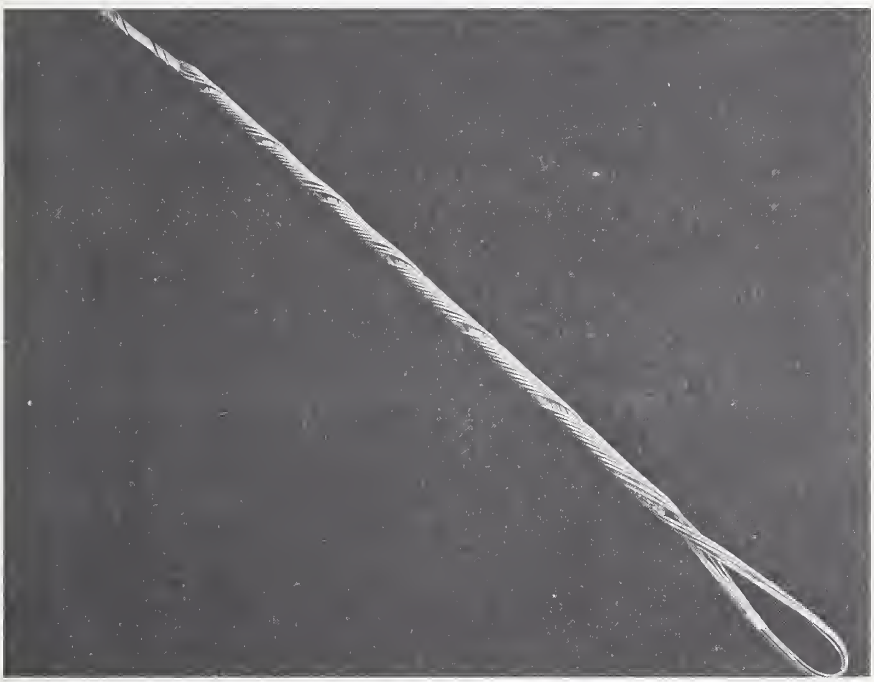


Figure 3 - Type F/A end fitting.

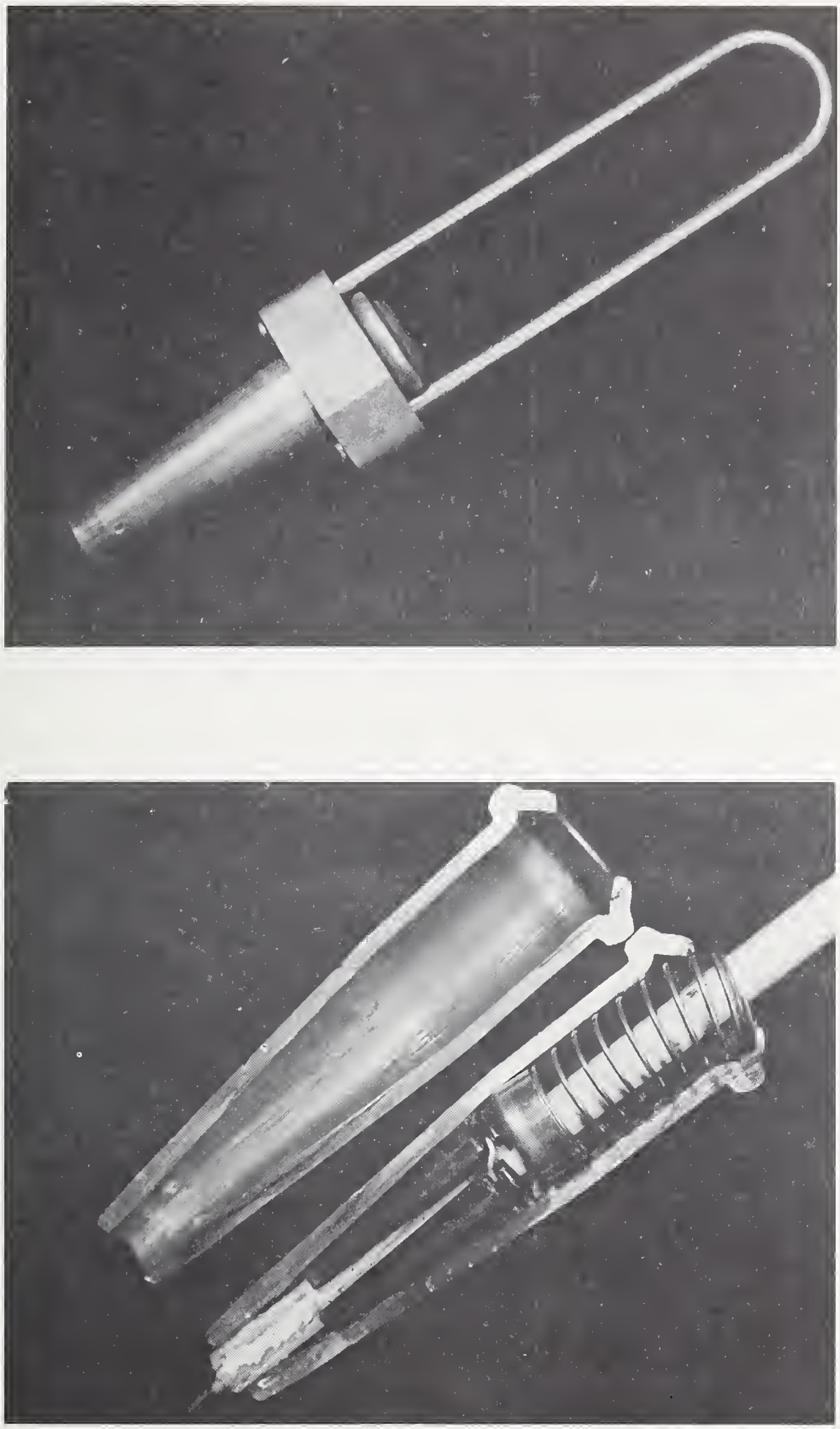


Figure 4 - Type R/V end fitting.

In this program the Type R/V fittings were used on Materials E and N rods. An attempt to use these fittings on a rope material (Material G) was unsuccessful; the rope slipped out of the fitting at a low tensile load.

The test results are given in Table 4. Failure in all cases was by a radial crushing of the rod, resulting in its being pinched off just inside the fitting.

3.5 Type R/P Fitting

The Type R/P fitting, Figure 5, is a basket-type, potted, conical compression fitting which is intended primarily for synthetic ropes such as Material G. The outward appearance of this fitting is quite similar to that of the Type R/V fitting. The conical basket, or potting head, is fitted with a yoke and bail for attachment to thimble-eye type hardware. The potting head and the yoke are aluminum alloy, the bail is stainless steel.

To mount the Type R/P fitting on Material G the polyurethane jacket was first removed from the end of the rope to a length somewhat less than that of the potting head. The strands of the rope were then untwisted and separated into individual rovings prior to potting.

In this program Type R/P fittings were also used on Material E rod specimens. In this application the end of the rod was slit into quarters, lengthwise, to a distance of an inch or two, and a conical aluminum-alloy wedge was driven axially into the center of the end to separate the quarters prior to potting.

The inner surface of the potting head was treated with a commercially available epoxy-release agent before potting. This permits the potted end to seat tightly into the conical potting head. This seating process is believed to result in significant radial compressive stresses being developed in the potted end. The epoxy-release agent also facilitates removal of the potting material for reuse of the head.

Several potting compounds were used in these tests. Type GS is a two-component, high-bond strength, epoxy resin system which is commercially available and is one of several recommended by the manufacturer of Material G for use with Type R/P fittings. It cures to a rather hard state in seven days at room temperature and, according to the resin manufacturer, exhibits the following mechanical properties:

Tensile shear strength, 3600 lbf/in^2

Compressive strength, 14000 lbf/in^2.

Table 4 - Tension Tests with Type R/V Fittings

Test No.	Material	Gripped length[a]	Free length	Maximum load[b]
		in	in	lbf
41032	E, 1/2-in dia	6	24	20,700
41033	E, 1/2-in dia	6	24	18,500
				19,600 average
41026	N, 1/2-in dia	6	24	21,000
41027	N, 1/2-in dia	6	24	20,200
				20,600 average

[a] Each end.

[b] Failure by pinching off.

Table 5 - Mechanical Properties of CW Series Potting Compounds

	Resin/activator ratio			
	2:3	1:1	3:2	2:1
Designation	C2W3	C1W1	C3W2	C2W1
Bond strength[a], lbf/in^2	2450	3280	-	-
Compressive strength[a], lbf/in^2	32200	20700	-	-
Elongation[a], percent	8.0	7.0	-	-
Elastic modulus[b], $lbf/in^2 \times 10^{-5}$	0.51	2.75	3.16	-

[a] According to the manufacturer.

[b] From compressive tests on 0.5-in diameter specimens performed in this laboratory.

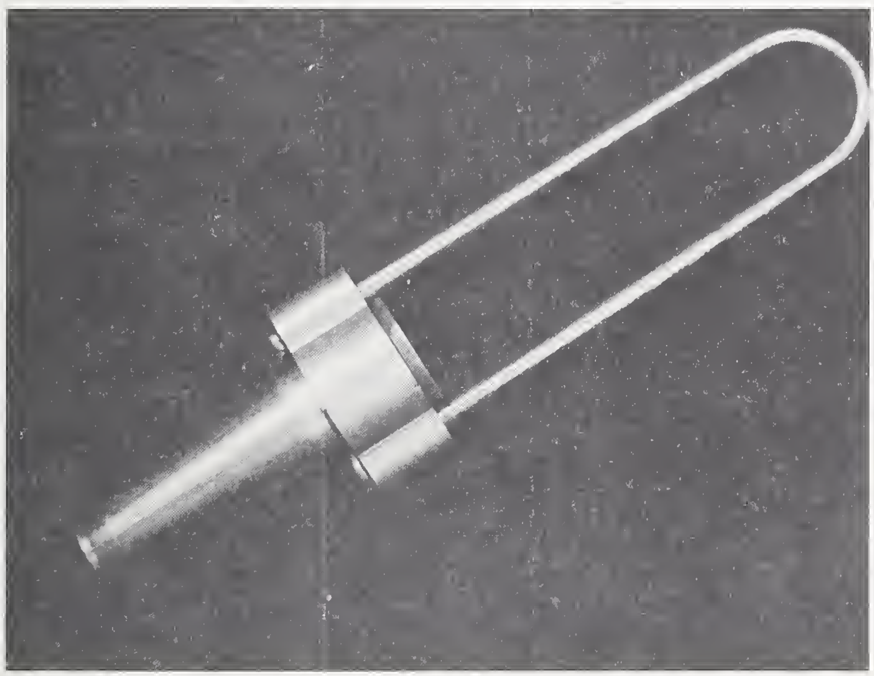


Figure 5 - Type R/P end fitting.

A second potting compound, also available commercially, was selected on the basis of previous work at this laboratory. It is a 100-percent-reactive, epoxy resin adhesive which requires an activator and a 2-h cure at 165 °F. This material may be formulated with different resin/activator ratios to provide different mechanical properties. The designations and some of the properties for several mixture ratios are given in Table 5.

On the basis of analytical considerations to be discussed later, it was felt that best results might be obtained through the use of a combination of two potting compounds in the potting head. Therefore, several tests were performed with Material E rod in which half of the head (the narrow end) was filled with a soft potting compound, C2W3, and the balance was filled with a harder compound, C1W1. The idea was to reduce the peak shear stress on the surface of the rod where it enters the potting head and yet retain substantial bond strength between the potting compound and the rod.

The test results are given in Table 6. The Material E specimens failed by pulling out of the Type R/P fittings. This is a rather complex process, involving various combinations of shear at the interface between the rod and the potting compound, crushing of the potting compound, and tensile failure of the rod in the vicinity of the conical wedge.

Although only one specimen of Material E was tested with the C2W3 potting compound, the results suggest that this formulation provides greater strength than is obtained with the combination of two potting compounds. In none of these tests of Material E was the true tensile strength of the rod approached.

Failure of Material G with the GS potting compound occurred by the individual strands breaking in rapid succession immediately adjacent to the end fitting. It appeared that the failures were the result of combined tension and torsion. The rope has a tendency to twist as the tensile load is applied, but this tendency was restrained by the end fitting which was not free to rotate in the testing machine.

With the C1W1 potting compound the first Material G specimen tested also failed strandwise at the end fitting. However, the next three specimens failed by crushing, resulting in a pinching-off just inside the end fitting.

With the C2W3 potting compound strandwise failures were again experienced, but in one case this failure took place in the free length of the specimen rather than at the fitting. It is believed, therefore, that the maximum load in this test, 19800 lbf, is close to the true tensile strength of the material.

Table 6 - Tension Tests with Type R/P Fittings

Test No.	Material	Potting compound	Gripped length (a) in	Free length in	Maximum load lbf	Failure
51061	E, 1/2-in dia	Note (f)	6	5	24500	(b)
51062	E, 1/2-in dia	Note (f)	6	5	20400	(b)
51063	E, 1/2-in dia	Note (f)	6	5	21900	(b)
71165 (g)	E, 1/2-in dia	Note (f)	6	42	18150	(b)
					21200 average	
71178	E, 1/2-in dia	C2W3	6	42	25150	(b)
42048	G, 7/16-in dia	GS	7	34	10000	(c)
42049	G, 7/16-in dia	GS	7	34	9700	(c)
42050	G, 7/16-in dia	GS	7	34	9900	(c)
					9900 average	
42054	G, 7/16-in dia	C1W1	7	34	13000	(c)
56090	G, 7/16-in dia	C1W1	7	21	12900	(d)
56091	G, 7/16-in dia	C1W1	7	20	12900	(d)
56092	G, 7/16-in dia	C1W1	7	19	15700	(d)
					13600 average	
71186 (g)	G, 7/16-in dia	C2W3	7	27	18000	(c)
71190 (g)	G, 7/16-in dia	C2W3	7	11	19800	(e)
					18900 average	

(a) One end.
(b) Pullout.
(c) Strandwise at the fitting.
(d) Pinch-off.
(e) Strandwise in the free length.
(f) C2W3 in narrow half of potting head, balance C1W1.
(g) Tested at slow crosshead speed.

Of the three potting compounds tried with Material G, C2W3 gave the highest breaking loads while GS gave the lowest.

Tests of 7-strand Material A and 1/2-in Material N were performed in an earlier investigation [10] using Type R/P fittings and C1W1 potting compound. In four tests of Material A, one specimen pulled out of the fitting prematurely and the other three showed an average strength of 17300 lbf. Similarly, in three tests of Material N, one specimen pulled out prematurely and the other two showed an average strength of 21200 lbf.

3.6 Summary

Table 7 summarizes the average breaking loads of each of the specimen materials with each of the end fittings and potting compounds with which it was tested. Data from the earlier investigation [10] are included. The load values are given to the nearest 1000 lbf. While the number of tests performed is less than would be necessary for statistical confidence, the table suggests the following tentative conclusions:

1. The two types of dead-end fittings, Type P and Type F, appear to function about equally well.

2. The Type R/V fitting provides about the same tensile strength with either of the two rod materials, Material E and Material N.

3. The C2W3 potting compound appears to be the best of those used with the Type R/P fitting.

4. The three types of fittings used on 7-strand Material A (Type P, Type F, and Type R/P with C1W1 potting compound) provide essentially equal strengths with this material.

5. The Type P fitting, the Type F fitting, and the Type R/P fitting with C2W3 potting compound appear to provide essentially equal strengths with Material E. The Type R/V fitting is inferior with this material.

6. The Type F/A fitting provides the highest strengths with Material G. The Type R/P fitting with C2W3 potting compound is nearly as good.

7. The four types of fittings used on Material N (Type P, Type F, Type R/V, and Type R/P with

Table 7 - Summary of Average Breaking Loads (in lbf x 10^{-3}) with Commercial End Fittings

		Material			
Fitting	Potting compound	A, 7-strand	E, 1/2-in dia	G, 7/16-in dia	N, 1/2-in dia
P	-	17	26	-	20
F	-	15	26	-	19
F/A	-	-	-	22	-
R/V	-	-	20	-	21
R/P	GS	-	-	10	-
R/P	C1W1	17	18	14	21
R/P	C2W3	-	25	19	-
R/P	C1W1 and C2W3	-	21	-	-

C1W1 potting compound) provide essentially equal strengths with this material.

4. DEVELOPMENT OF IMPROVED END FITTINGS

The specific objective of this task was to develop end fittings that can attain or approach the true tensile strengths of available GRP rod and rope materials. In order to accomplish this objective, an analytical parameter study of the problem and an experimental evaluation of trial prototype fittings were pursued concurrently. The analytical study involved the axisymmetric, finite-element stress analysis of a broad class of end connections consisting of a metal sleeve joined to the GRP rod with a polymeric potting material. The experimental study involved the fabrication and tensile testing of prototype end fittings employing several different gripping concepts. An important aspect of this parallel analytical and experimental approach was the free transfer of newly developed information from one study to the other. During the course of the work the orientation of each study was changed to a more profitable direction based on information developed in the other study. Some aspects of the analytical study were reported in greater detail elsewhere [11].

4.1 Finite-Element Analysis

A new computer program was developed for the axisymmetric, finite-element stress analysis of end connections. The basic finite-element formulation used [12] was developed for the case of isotropic elastic materials. That earlier formulation has been modified in the end-fitting analysis in accordance with the assumption that the GRP rod is homogeneous and transversely isotropic as defined by five independent elastic constants. The materials of the metal sleeve and the potting compound are assumed to be isotropic elastic.

In a finite-element analysis the continuum is subdivided into a network of elements that are connected to adjacent elements only at common nodal points. Elastic displacements within the individual elements are defined by generalized functions that assure displacement compatibility along common boundaries of adjacent elements. In the end-fitting analysis elastic strains within the elements are assumed to be uniform, thus assuring displacement compatibility along common element boundaries.

Figure 6 shows a representative finite-element analysis mesh for one general class of end connections. In this case, the metal sleeve is conically tapered, and the outer end of the GRP rod is slit into quarters and spread with a conical metal wedge. Where the rod is spread by the wedge, the elastic constants for the region occupied by the

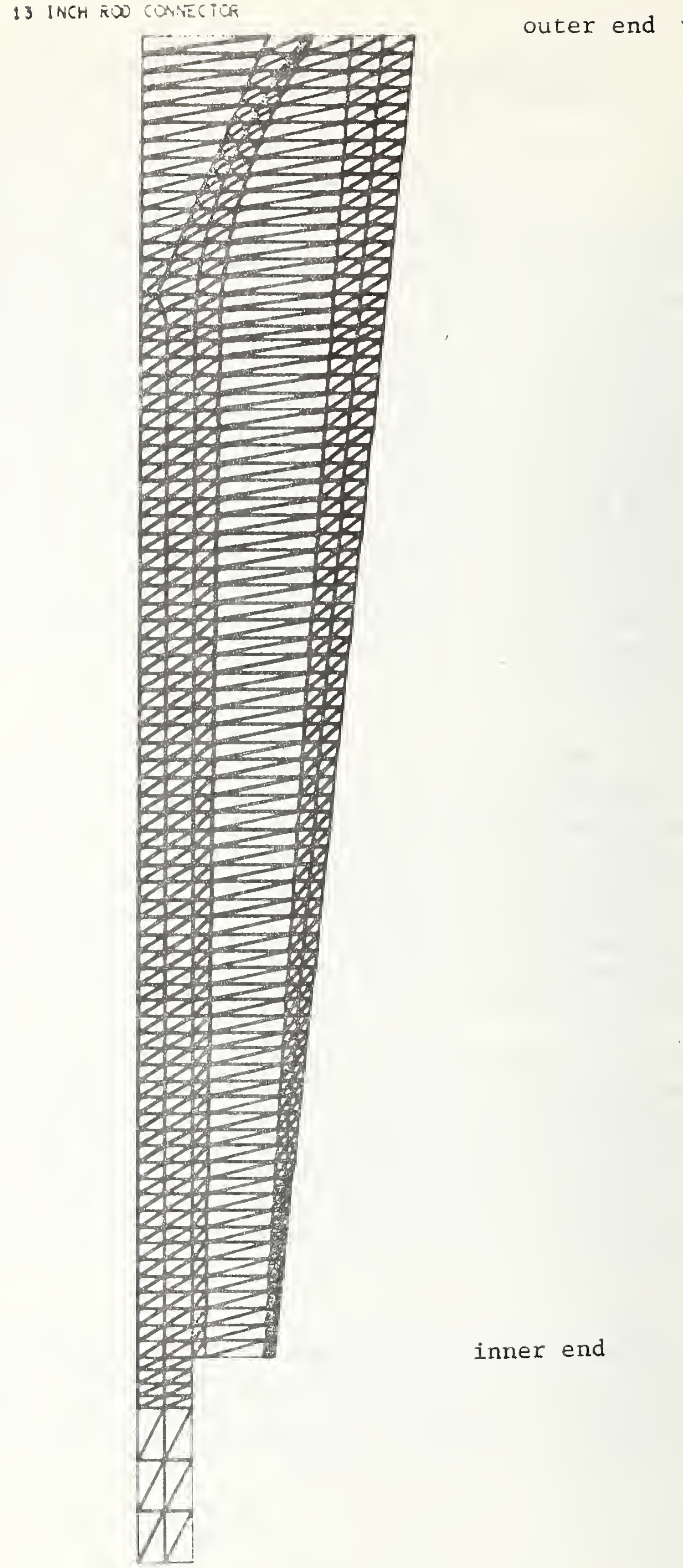


Figure 6 - Representative finite-element mesh for one general class of end fittings.

spread rod are recomputed according to the volume fractions of rod material and potting compound.

In addition to generating the usual line-printer output of computed results, the computer program drives an electron-beam plotter which produces contour plots of seven different stress components and the angle of maximum principal stress, as well as a plot of the analysis mesh. As an example, Figures 7, 8 and 9 give, respectively, plots of the analysis mesh, the longitudinal normal stress and the longitudinal shear stress for the Mod 4 end fitting which was studied in the experimental stress analysis described later.

4.2 Analytical Parameter Study

The linear elastic finite-element computer model was used in a parameter study of the general class of end fittings represented schematically in Figure 10. The numerals in the figure denote the eight variable parameters studied. Parameters 4 and 5 are the elastic moduli of the two potting compounds indicated.

It was assumed that the critical component of stress, with respect to tensile strength, is the peak bond-shear stress at the interface between the rod and the potting compound. This assumption was based on the fact that rod pullout was the most common failure mode observed in tensile tests of this class of fitting.

The analyses were carried out for a 1/2-in diameter GRP rod. The assumed properties of the metal sleeve and the conical wedge (not shown) were those of 7075-T6 aluminum alloy.

The general indications for the eight parameters studied are:

1. End-fitting length.--Within the range of 6 to 16 in, greater length results in significantly smaller peak bond-shear stress, but the rate of change of peak stress decreases as length increases.

2. Potting thickness at inner end of fitting.--Within the range of 0.24 to 0.48 in, greater thickness results in significantly smaller peak bond-shear stress, but the rate of change of stress decreases as thickness increases.

3. Sleeve thickness at inner end of fitting.--Within the range of 0.02 to 0.25 in, greater thickness results in slightly greater peak bond-shear stress.

4. Elastic modulus of inner potting compound.--Within the range of 40000 to 316000 lbf/in^2, greater stiffness

of potting compound results in significantly greater peak bond-shear stresses. This is true whether a single potting compound or a combination of two different compounds is used.

5 and 6. Elastic modulus and length of outer potting compound.--A combination of two potting compounds having different elastic moduli produces two bond-shear stress peaks (one at the inner end of each potting compound). If parameters 4, 5 and 6 are proportioned so as to make the two stress peaks approximately equal, the peak stress is significantly less than for the case of a single potting material.

7 and 8. Potting thickness and sleeve thickness at the outer end of the fitting.--Parameters 7 and 8 have a relatively small direct influence on the peak bond-shear stress.

4.3 Experimental Prototype Fittings

Two gripping configurations investigated early in the experimental program gave disappointing results in tensile strength tests. One type of experimental fitting consisted of a cylindrical metal sleeve that was attached to the GRP rod with a thin layer of high-strength adhesive. Another type of experimental fitting consisted of a thick metal sleeve with a conical inside taper, potted to the GRP rod, and proportioned to provide a relatively small thickness of potting material at the inner end of the fitting. According to the finite-element analysis each of these two concepts is characterized by a very high peak bond-shear stress at the inner end of the fitting. Subsequent to these early results, experimental fittings were designed to provide for a relatively thick cushion of potting material at the inner end of the fitting.

A 6.5-in long experimental fitting (Mod 1), designed on the basis of early results of the analytical study, is shown in Figure 11. The highest strength attained with a Mod 1 fitting was 16240 lbf. At failure in that test, one quarter of the 1/2-in Material N rod failed in tension near the inner end of the conical wedge and the epoxy coating on the rod sheared off as the rod pulled out of the fitting.

A 12-in long experimental fitting (Mod 2), similar in concept to the Mod 1 fitting, is shown in Figure 12. The highest tensile test load applied to a Mod 2 fitting was 18150 lbf. In that test the Type R/P fitting (with C1W1 potting compound) on the other end of the 1/2-in Material E rod failed in the pullout mode. The Mod 2 fitting is comparatively expensive to fabricate, and removal of the potted material from the fitting, for reuse of the fitting, proved to be rather

ENDFIT LENGTH	12.400	ADH LENGTH	11.4, 12.40	ROD RADIUS	.260	MAY 24, 1972	
ENDFIT THICK.	.100	ADH THICK.	.365, .115	Z-LOAD	25000.		
E11, ROD	.70000000+07	E22, ROD	.20760000+07	E, METAL	.10300000+08	V12, METAL	.330
V12, V13, ROD	.253	G12, ROD	.78580000+06	E, ADHES	.51000000+05	V12, ADHES	.350

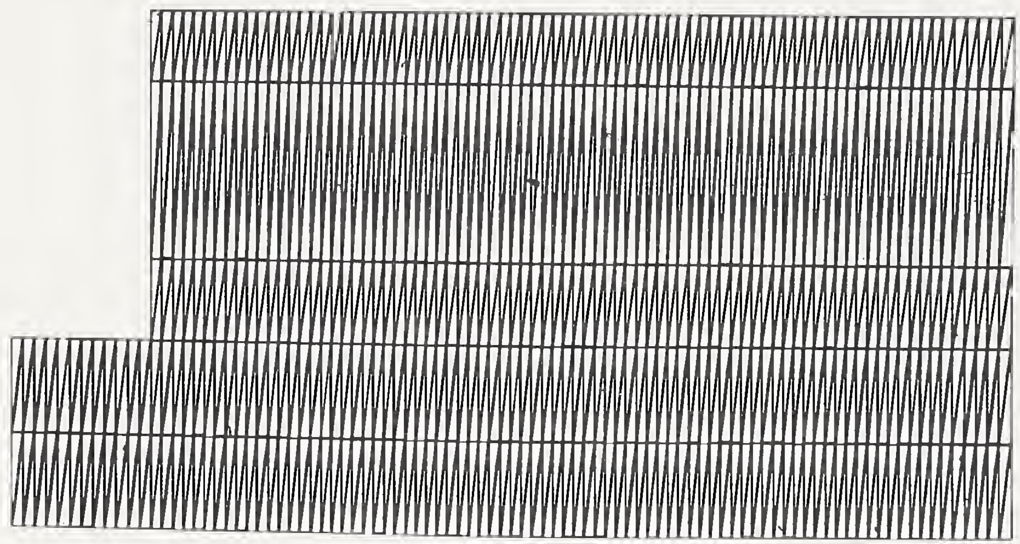


Figure 7 - Finite-element mesh for a Mod 4 end fitting.

ENDFIT LENGTH	12.400	ADH LENGTH	11.4, 12.40	ROD RADIUS	.260	MAY 24, 1972		U1108/SC4020 0006 0006
ENDFIT THICK.	.100	ADH THICK.	.365, .115	Z-LOAD	25000.			
E11, ROD	.70000000+07	E22, ROD	.20760000+07	E, METAL	.10300000+08	V12, METAL	.330	
V12, V13, ROD	.293	G12, ROD	.78580000+06	E, ADHES	.51000000+05	V12, ADHES	.350	

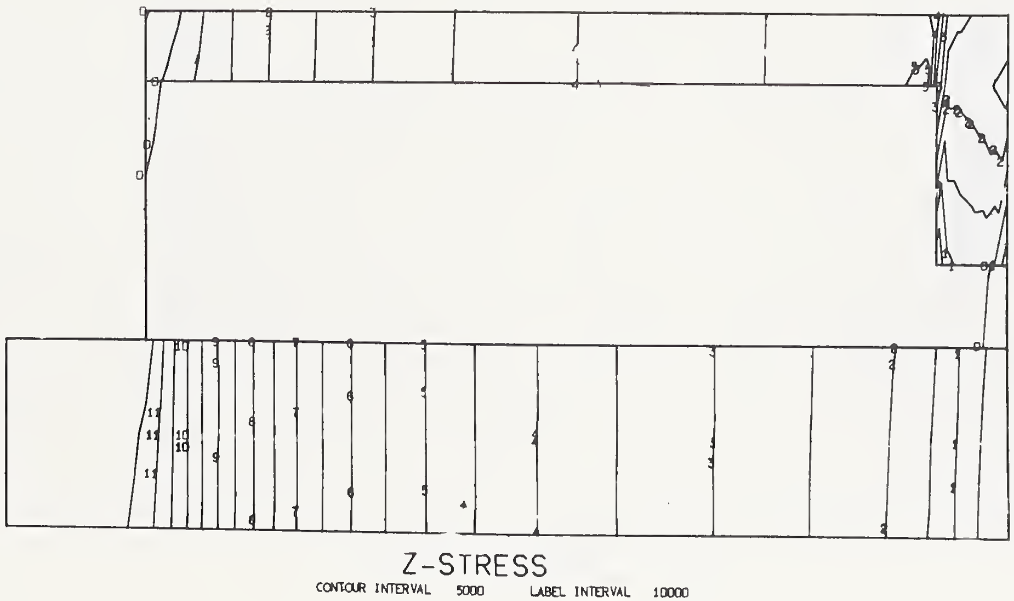


Figure 8 - Contour plot of the longitudinal normal stress in a Mod 4 end fitting.

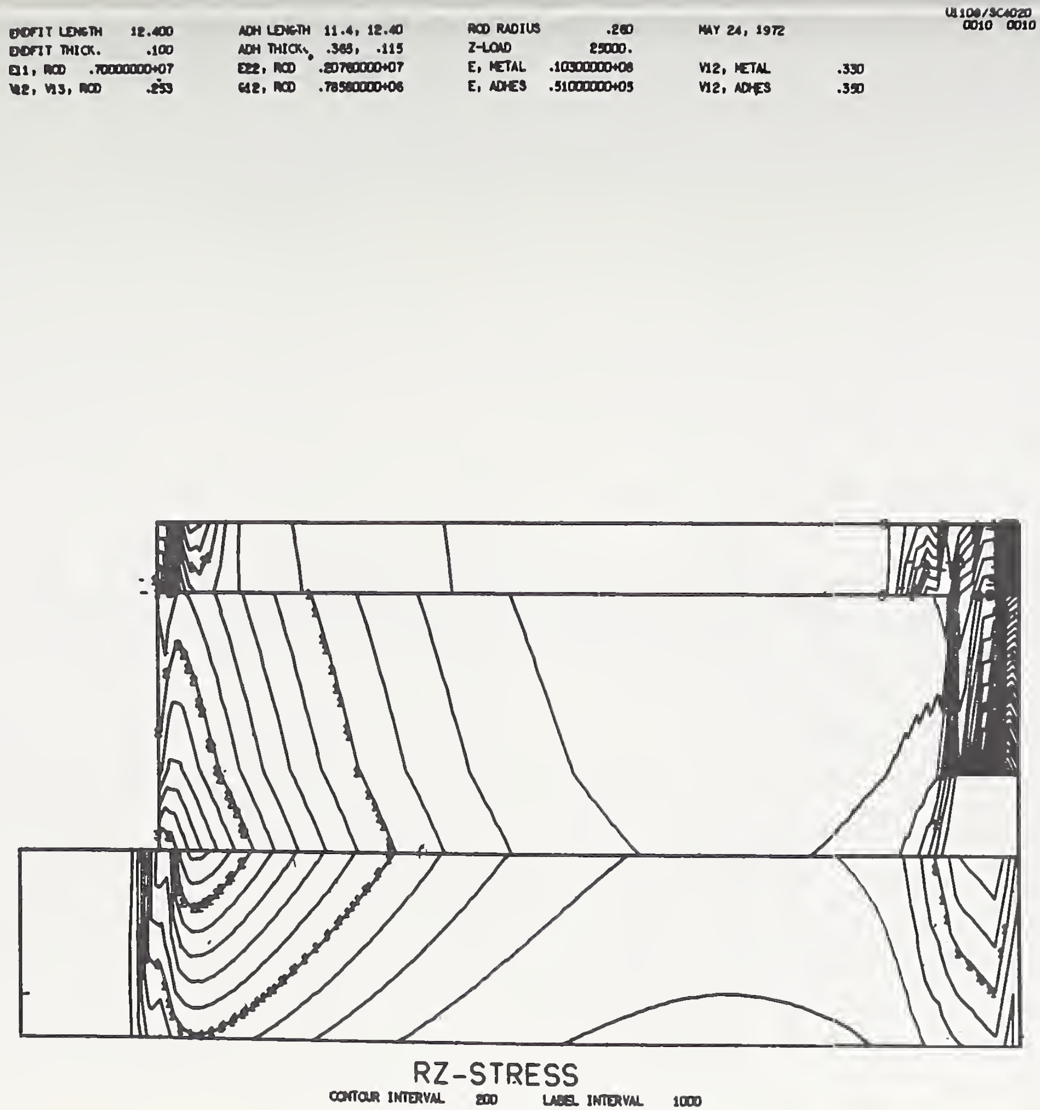


Figure 9 - Contour plot of the longitudinal shear stress in a Mod 4 end fitting.

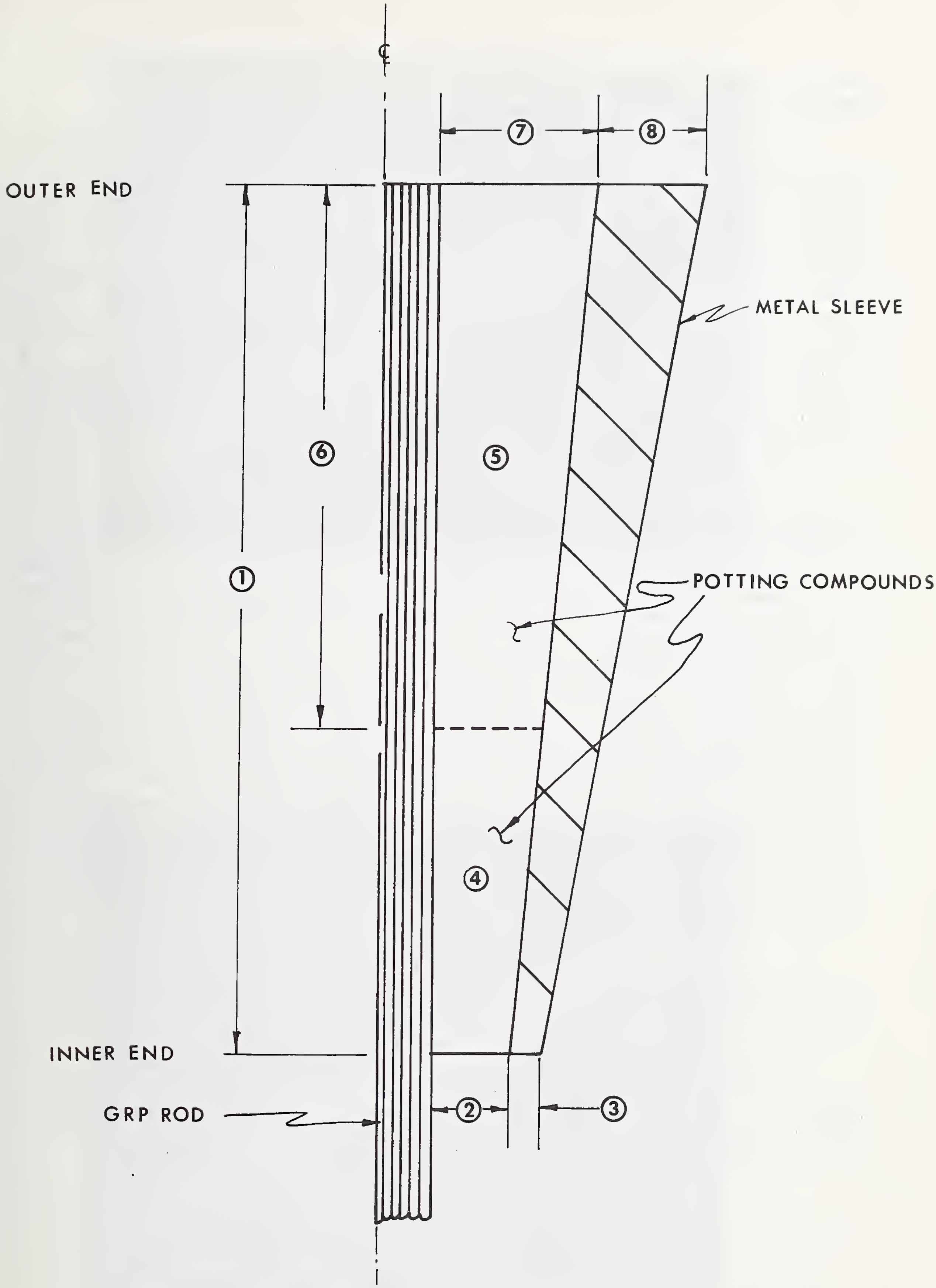


Figure 10 - Parameters for one general class of end fittings.

difficult due to the thin wall. Further evaluation of this fitting was, therefore, deferred indefinitely.

An experimental fitting (Mod 3), consisting of a cylindrical metal sleeve attached to the GRP rod with a thick layer of potting material, is shown in Figures 13 and 14. This fitting consists of a 1 1/2-in diameter rod of 7075-T6 aluminum alloy, 12 in long, which is drilled out axially to a depth of 7 in with a 3/4-in drill. This hole is then counterbored to a depth of 6 in, leaving a uniform 1/8-in wall thickness. When used with GRP rod material the end of the rod, after abrasive cleaning, is set into the 3/4-in hole in the base of the cavity, and the rod is carefully aligned parallel and concentric with the fitting while the remaining cavity is filled with the potting compound. With GRP rope material the jacket, if any, is first removed from the end of the rope to a length of about 11 in and the strands are untwisted and cleaned prior to potting. The 3/4-in hole at the base of the cavity is not used with the rope materials.

The Mod 3 fitting was used for a series of twelve tests to determine the relative bond-shear strengths of four different potting compounds when used in this configuration with 1/2-in Material E rod. The four potting compounds were made of the same two constituents mixed in different ratios of resin to activator to give four different degrees of stiffness (Table 5). The GRP rods were not slit or wedged and only one potting compound was used in each test. All twelve specimens failed by rod pullout and the results are given in Table 8. Although there is great scatter in these data, the relatively high strengths of the specimens with the most flexible potting compound are significant. Finite-element analyses of the Mod 3 fittings, for the three potting compound moduli given in Table 8, indicate that a more flexible potting compound produces a significantly lower peak bond-shear stress. According to the analyses, the peak bond-shear stress with the most flexible C2W3 potting compound is only 47 percent of the corresponding stress with the stiff C3W2 compound. The strong dependence of peak bond-shear stress on potting compound stiffness is apparently a major factor in the relatively high maximum loads developed with the low-modulus potting compound.

The Mod 3 concept was also evaluated in four tests using 7/16-in GRP rope (Material G) and the low-modulus C2W3 potting compound. The results of these tests are given in Table 9.

The greatest success thus far has been experienced using the experimental Mod 4 end fitting shown in Figures 13 and 14. This end fitting is essentially identical to the Mod 3 fitting except that the potted length is increased to 13 in.

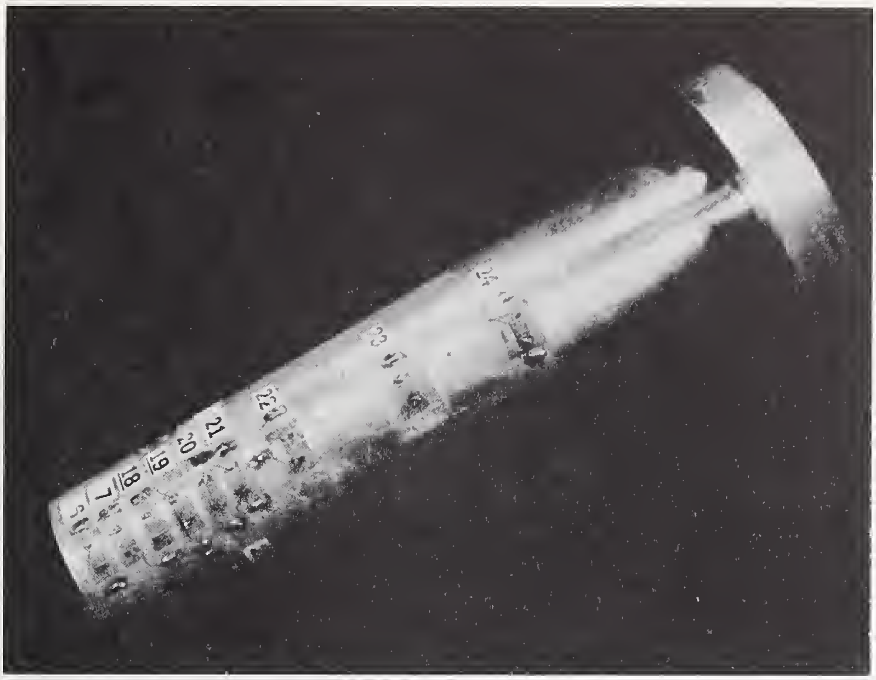


Figure 11 - Mod 1 experimental end fitting.

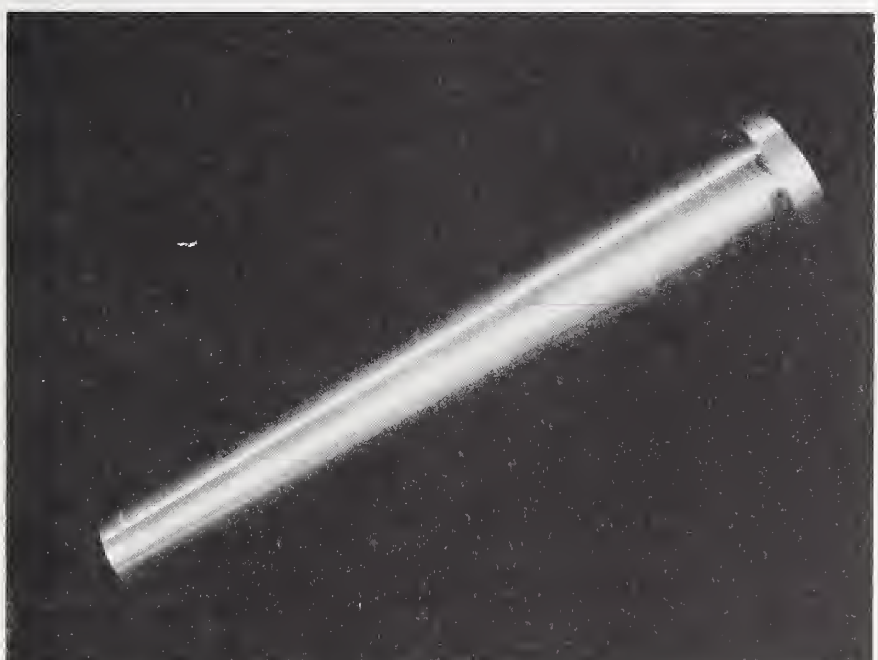


Figure 12 - Mod 2 experimental end fitting.

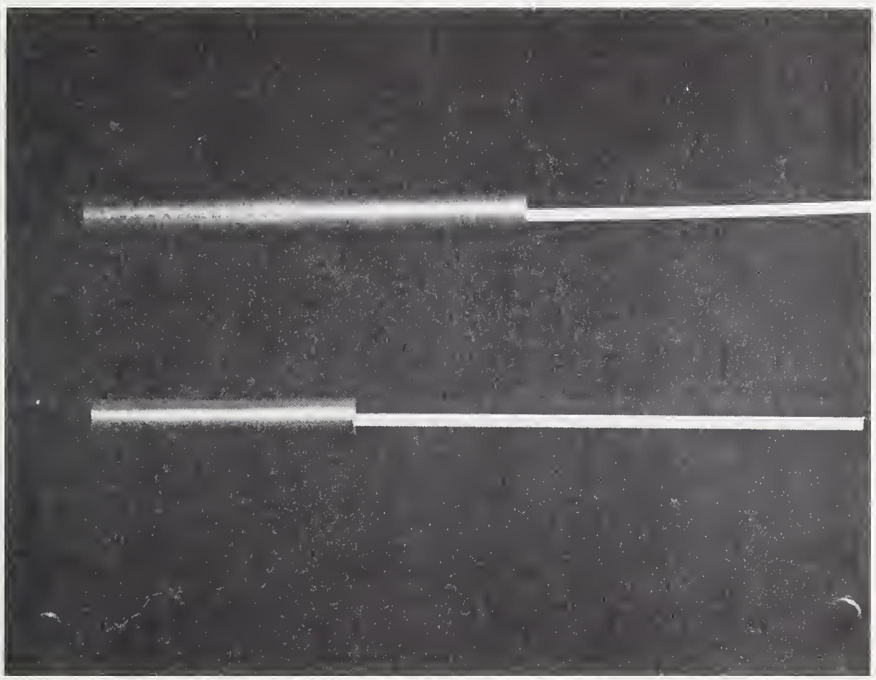
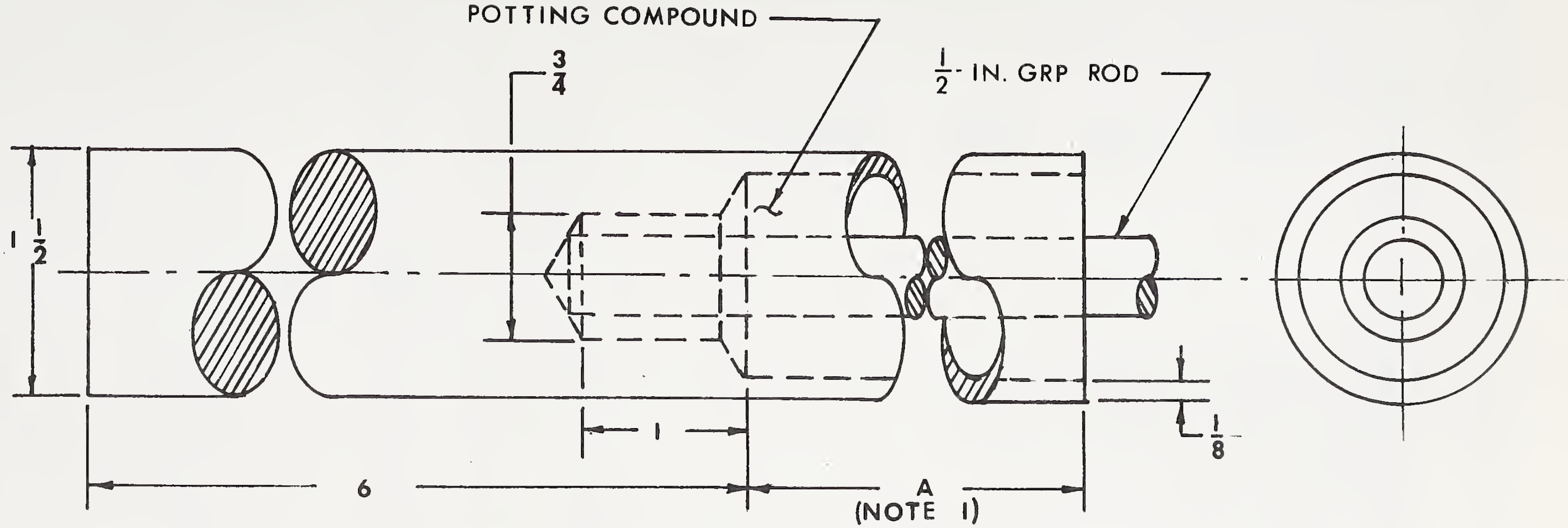


Figure 13 - Mod 4 (above) and Mod 3 experimental end fittings.



Note 1. For Mod 3 fitting A = 6; for Mod 4 fitting A = 12.

Figure 14 - Schematic drawing of Mod 3 and Mod 4 experimental end fittings.

Table 8 - Tensile Tests with Mod 3 Fittings on 1/2-in Material E

Test No.	Potting compound[a] Designation	Elastic modulus	Maximum load
		lbf/in^2	lbf
71169	C2W3	0.51×10^5	19850
71170	C2W3	0.51	15500
71171	C2W3	0.51	18650
Average:			18000
71166	C1W1	2.75	12200
71167	C1W1	2.75	8500
71168	C1W1	2.75	19250
Average:			13300
71172	C3W2	3.16	8000
71173	C3W2	3.16	14350
71174	C3W2	3.16	9400
Average:			10600
71175	C2W1	-	12350
71176	C2W1	-	17500
71177	C2W1	-	18100
Average:			16000

(a)See Table 5.

Table 9 - Tension Tests with Mod 3 Fittings on 7/16-in Material G
Potting compound: C2W3

Test No.	Maximum load	Failure
	lbf	
71185	15600	(a)
71187	16600	(b)
71188	17400	(a)
71189	17300	(c)

(a)Pullout.

(b)Inside fitting.

(c)Strandwise at the fitting.

4.4 Experimental Stress Analysis

A specimen consisting of two Mod 4 end fittings attached to a 1/2-in Material E rod was instrumented with twenty-six resistance strain gages and subjected to six cycles of tensile loading. The loading sequence was 0-2500-0-10000-0-10000-0-22000-0-23250-0-30100 lbf (failure). Seventeen strain gages were located on the surface of one end fitting and the remaining nine gages were mounted on the GRP rod adjacent to that fitting. Twenty-two gages were oriented in the longitudinal direction and nine of these were grouped in sets of three and spaced 120° apart to detect eccentricity. Four gages were oriented in the circumferential direction. The 7075-T6 aluminum alloy sleeve was filled, to within 0.6 in of the inner end, with the low-modulus C2W3 potting compound.

Figures 15 and 16 are plots of longitudinal strain on the surface of the instrumented fitting as predicted by the linear elastic finite-element analysis and as measured by the strain gages. The individual data points indicate the strains measured during the initial application of the particular load indicated. The vertical lines in Figure 16 indicate the spread in strain data for subsequent loading cycles. The major part of the spread is due to residual strain present in the specimen at the beginning of Load Cycles 3 and 5. Those two cycles were applied less than one hour after completing Load Cycles 2 and 4, (which had maximum values of 10000 lbf and 22000 lbf, respectively) and the strain gages had not been reset to zero. There is good agreement between the linear elastic analysis and the experiment at 1000 lbf load during the first cycle, but there is progressively poorer correlation at higher loads.

The rate of change of surface strain with respect to distance along the fitting is approximately proportional to the rate of transfer of load in shear through the potting compound. That is, the slope of a smooth curve fitted to a set of strain data points in Figures 15 or 16 would be approximately proportional to the bond-shear stress acting at the surface of the rod. This interpretation of the data suggests that, at the higher loads and for the greater part of the potted length of the rod, the bond-shear stress acting on the rod was roughly uniform. This apparent degree of uniformity of bond-shear stress is believed to be a major factor contributing to the relatively high strength of the Mod 4 type fitting when used with the flexible C2W3 potting compound.

4.5 Tensile Tests with Mod 4 Fittings

The results of twenty-one tensile tests using Mod 4 fittings on three different rod and rope materials are given in Table 10. The low-modulus C2W3 potting compound was used on all twenty-one specimens. The average maximum load for the fifteen specimens of 1/2-in Material E was

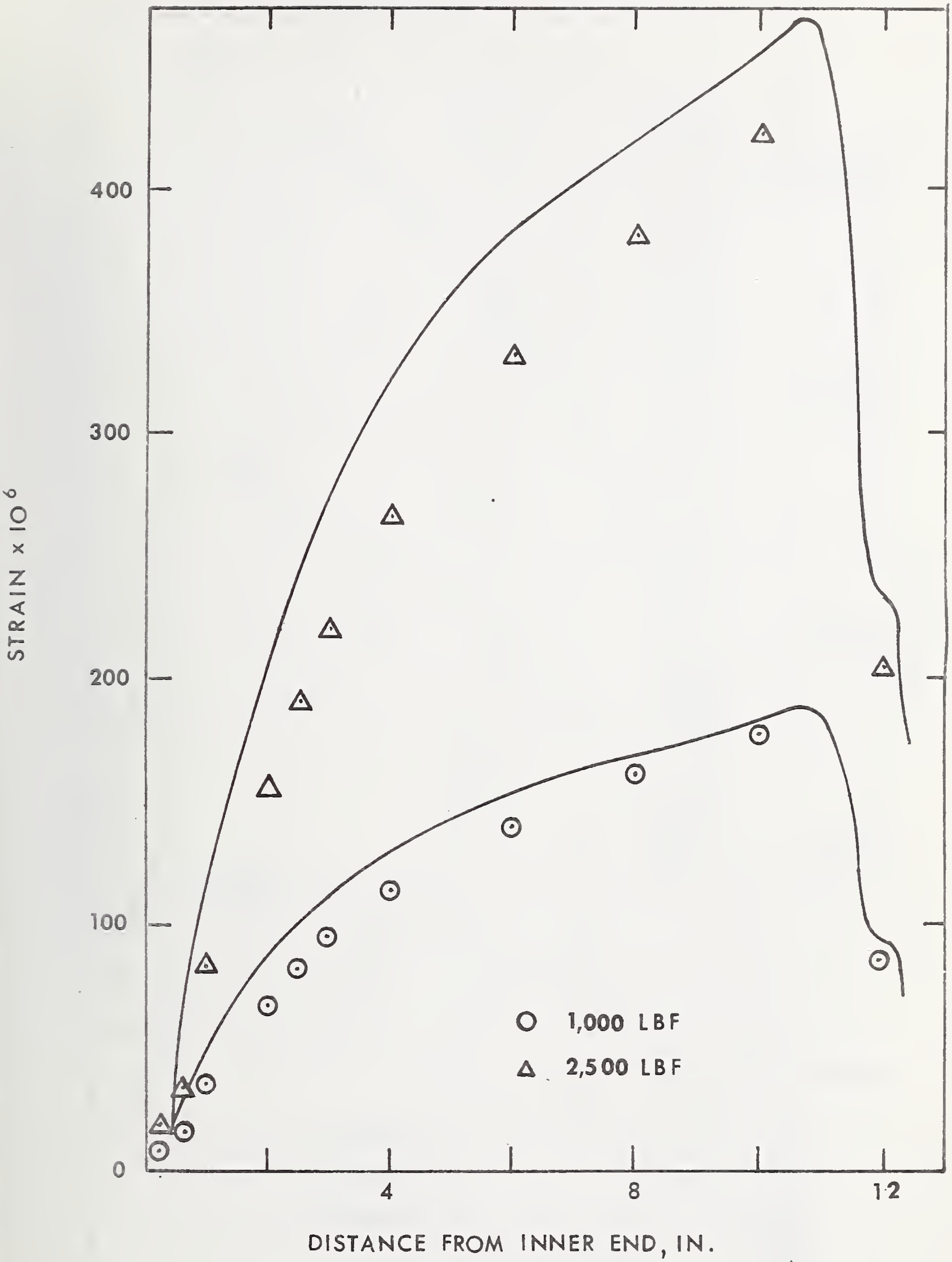


Figure 15 - Longitudinal normal strain on the outer surface of a Mod 4 end fitting, low tension loads.

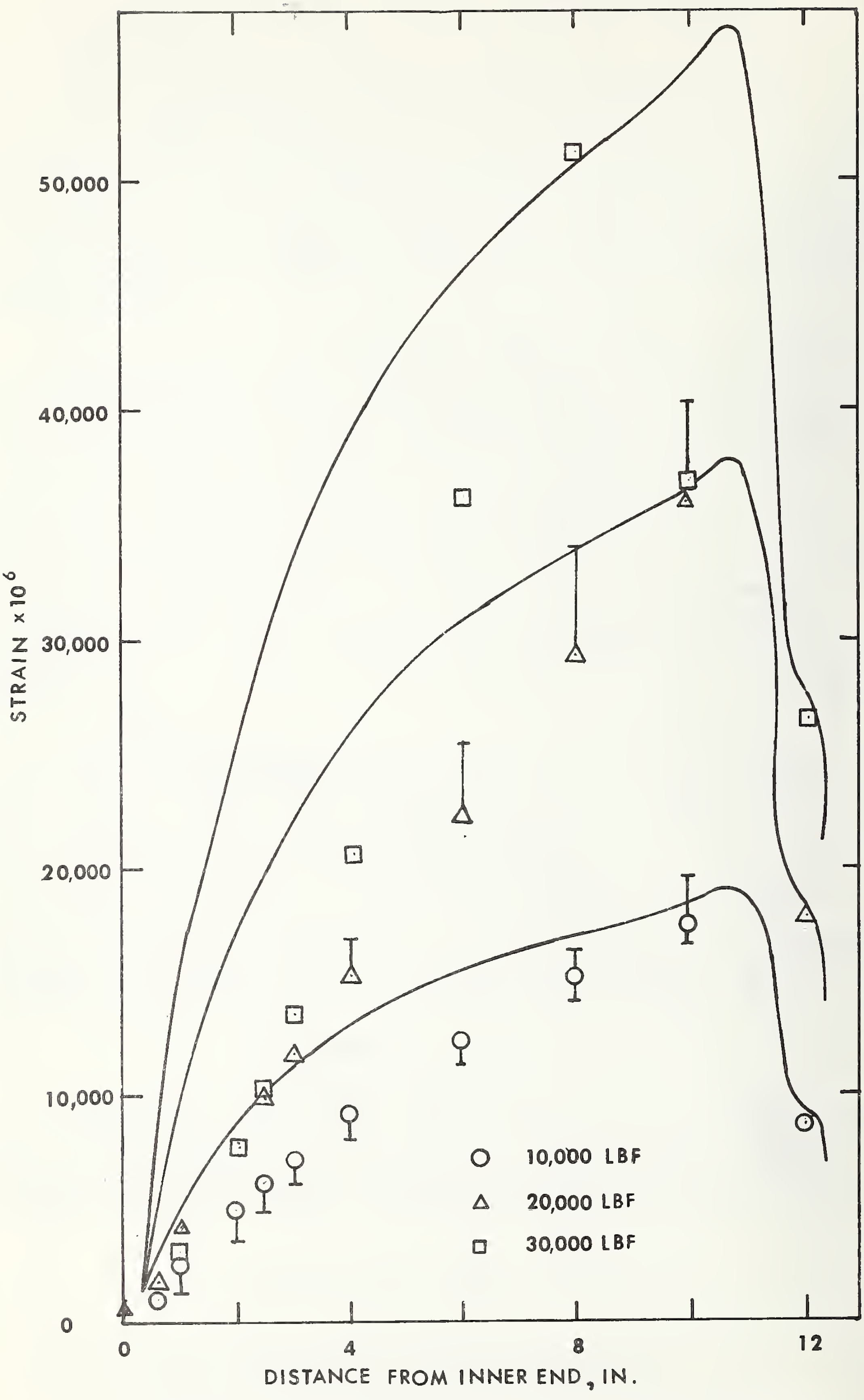


Figure 16 - Longitudinal normal strain on the outer surface of a Mod 4 end fitting, high tension loads.

Table 10 - Tension Tests with Mod 4 End Fittings
Potting compound: C2W3.
Gripped length: 12 in, each end.

Test No.	Material	Nominal diameter	Maximum load	Failure
		in	lbf	
71182	E	1/2	31350	(a)
71183	E	1/2	32850	(b)
71184	E	1/2	25750	(a)
81242	E	1/2	27000	(a)
81243	E	1/2	28600	(a)
81244	E	1/2	32600	(a)
81245	E	1/2	29600	(a)
81246	E	1/2	29000	(a)
81247	E	1/2	31800	(a)
81248	E	1/2	32750	(a)
81249	E	1/2	30950	(a)
81250	E	1/2	31100	(a)
81251	E	1/2	31500	(a)
91261	E	1/2	23250	(a)
101315	E	1/2	30100	(a)
Average:			29900	
71190	G	7/16	19800	(b)
81239	G	7/16	20250	(c)
92271	G	7/16	21200	(b)
Average:			20400	
81240	N	1/2	23700	(a)
81241	N	1/2	17850	(a)
91263	N	1/2	18900	(a)
Average:			20100	

[a] Pullout.

[b] Failure in the free length.

[c] Strandwise in the fitting.

29900 lbf, corresponding to a nominal mean stress of 153000 lbf/in^2. One of these specimens failed at 32850 lbf in a tensile mode in its free length, several inches from the fitting. This indicates that the true tensile strength of the 1/2-in Material E is approached with the Mod 4 fittings. The other fourteen Material E specimens failed by pullout with the failure located principally at the interface between the rod and the potting compound.

The average maximum load for three specimens of 1/2-in Material N with Mod 4 end fittings was only 20100 lbf, corresponding to a nominal mean stress of 103000 lbf/in^2. Failure here was also by pullout but in this case the failure was within the rods with several of the outer layers of glass fibers being sheared off. However, in a test of 1/4-in Material N, which will be discussed later, failure occurred in the free length at a nominal mean stress of 154000 lbf/in^2. This suggests that a longer end fitting of the Mod 4 type would more nearly approach the true tensile strength of 1/2-in Material N rod.

The average maximum load for three 7/16-in Material G rope specimens tested with Mod 4 fittings was 20400 lbf.

A comparison of these results with those obtained with commercial end fittings (Table 7) reveals that the Mod 4 end fitting is clearly superior to the commercial types for Material E. For Material N the performance of the Mod 4 fitting is equal to that of the commercial types. For Material G the Mod 4 fitting is superior to all of the commercial types except the Type F/A fitting. It thus appears that there is no single type of end fitting which is best for all of the materials. This is not an entirely unexpected finding since it is reasonable to expect different behavior from rod and rope materials. However, it also appears that different rod materials also require different gripping techniques for optimum performance.

5. DENSITY

The percentage glass content in GRP rod and rope can vary not only between manufacturers but, conceivably, between batches produced by a single manufacturer. For this reason it was considered desirable to investigate the variations of tensile strength, modulus of elasticity and density with diameter. The study of density is described here; the studies of tensile strength and modulus of elasticity are presented in subsequent sections of this report.

5.1 Material A

Small samples of single-strand Material A were carefully weighed in air and in water. The densities and the specific gravities of the

samples were determined from these weighings and the known densities of ambient air and water. The results of these measurements and calculations are given in Table 11. The table also gives the calculated weights per foot of the materials, based on the nominal diameters which, for Material A, are close to the actual diameters.

As a check on the method, the density of the 0.119-in material was also calculated from weight, length and diameter measurements made earlier [10]. The average density so determined agrees exactly with the value obtained in the present work.

The nominal specific gravity of Material A reported by its manufacturer is 1.93 ± 0.17. All of the values listed in Table 11 fall within this range except that for the smallest size. However, the weight-per-foot values given in the table are all within the ranges specified by the manufacturer for the various sizes.

The data do not show any consistent variation of density with diameter.

5.2 Material E

The specific gravity and density of two samples of 1/2-in Material E were calculated from weight, length and diameter measurements. The two determinations agreed within one percent and showed a specific gravity of 1.99 and a density of 0.0719 lb/in^3. The calculated weight of 1/2-in Material E rod, based on the actual diameter, is 0.192 lb/ft.

Measurements made earlier [10] on 13/16-in Material E show a specific gravity of 1.88 and a density of 0.0677 lb/in^3.

5.3 Material G

Density measurements were made on three types of Material G samples: unjacketed rope, single strand, and single roving. The method of measurement was the same as that described above for Material A. The results are given in Table 12.

The results show that

1. there is variability in the densities of nominally identical specimens, suggesting a certain amount of nonuniformity of composition,

2. the differences in density as measured on rovings, strands and rope are comparable to those observed on nominally identical specimens, suggesting that there is no systematic difference in the densities of the three forms, and

Table 11 - Density of Material A

Test No.	Nominal diameter	Specific gravity	Density	Weight per ft
	in		lb/in^3	lb/ft
62120	0.031	1.72	0.0621	0.000562
62121	0.043	1.94	0.0701	0.00122
62122	0.063	1.77	0.0640	0.00241
62123	0.084	1.77	0.0640	0.00426
62124	0.119	1.92	0.0694	0.00926
Average:		1.82	0.0657	

Table 12 - Density of Material G

Test No.	Nominal diameter	Specimen type	Specific gravity	Density	Weight per ft[a]
	in			lb/in^3	lb/ft
72191	5/16	single roving	1.85	0.0668	
72192	5/16	single roving	2.05	0.0741	
72193	5/16	single roving	1.81	0.0654	
Average:			1.90	0.0688	0.0634
72194	5/16	single strand	1.97	0.0711	
72195	5/16	single strand	2.04	0.0737	
72196	5/16	single strand	2.06	0.0744	
Average:			2.02	0.0731	0.0674
72197	7/16	single roving	1.94	0.0701	
72198	7/16	single roving	2.07	0.0748	
72199	7/16	single roving	1.89	0.0683	
Average:			1.97	0.0711	0.128
72200	7/16	single strand	1.93	0.0697	
72201	7/16	single strand	1.92	0.0694	
72202	7/16	single strand	1.91	0.0690	
Average:			1.92	0.0694	0.125
72203	5/8	bare rope	2.06	0.0744	
72204	5/8	bare rope	2.03	0.0733	
72205	5/8	bare rope	2.08	0.0752	
Average:			2.06	0.0743	0.274

[a] Bare rope.

3. there is no consistent variation in density with the diameter of the rope.

The measured values of specific gravity ranged from 1.81 to 2.08, which bracket the nominal value of 2.0 reported by the manufacturer.

The weights of the full-sized ropes, minus the jackets, were calculated from the averages of each series of density measurements. See Table 13. For this purpose the volume of the bare rope was calculated from the nominal diameter.

The weights of the jacketed ropes were also calculated (Table 13) by adding the weights of the jackets to the weights of the bare rope. Jacket weights were calculated from the nominal density (0.0451 lb/in^3) and thickness (0.015 in) of the jacket as reported by the manufacturer. In addition, the actual weight-per-foot values were calculated from direct measurements of the weight and length of long samples of Material G. These two determinations of the weight of Material G are compared in Table 13. Also given in this table are the rated values according to the manufacturer.

Comparison of the calculated and actual weights shows excellent agreement in the two smaller sizes but a substantial discrepancy in the largest size. This suggests that in the two smaller sizes the nominal diameter provides a good estimate of the actual cross sectional area of the bare rope, while in the 5/8-in size the actual cross sectional area is substantially smaller than this estimate.

Comparison of the actual weights of Material G with the manufacturer's rated values (Table 13) shows that the rated values are low in every case, particularly in the smaller sizes where the discrepancies are about 20 percent.

5.4 Material N

The densities of several sizes of Material N were calculated from weight, length and diameter measurements which were made on the coated material. The results are given in Table 14. The actual diameters of the coated rods were used to calculate the weights per foot.

The specific gravity of Material N, according to its manufacturer, is between 1.85 and 2.05. The values in Table 14 fall within this range except for the 1/4-in size. Earlier measurements of the 1/2-in size [10] gave average values of specific gravity, density and weight which agree with the present values within less than one percent.

Table 13 - Weight of Material G

Nominal diameter	Weight per foot				
	Calculated			Actual, jacketed rope	Rated[a]
	Bare rope	Jacket	Jacketed rope		
in	lb/ft	lb/ft	lb/ft	lb/ft	lb/ft
5/16	0.0654[b]	0.0080	0.0734	0.0732	0.061
7/16	0.126[b]	0.0112	0.137	0.140	0.116
5/8	0.274	0.0159	0.290	0.243	0.233

[a]According to the manufacturer.

[b]Average from measurements on strand and roving.

Table 14 - Density of Material N

Test No.	Nominal diameter	Specific gravity	Density	Weight per foot	
				Calculated	Rated
	in		lb/in^3	lb/ft	lb/ft
62108	1/4	1.70	0.0614		
62109	1/4	1.72	0.0621		
62110	1/4	1.72	0.0621		
Average:		1.71	0.0619	0.053	0.057
62111	3/8	1.97	0.0712		
62112	3/8	1.98	0.0715		
62113	3/8	1.96	0.0708		
Average:		1.97	0.0712	0.124	0.10
62114	1/2	1.99	0.0719		
62115	1/2	1.99	0.0719		
62116	1/2	1.99	0.0719		
Average:		1.99	0.0719	0.190	0.17
62117	5/8	2.03	0.0733		
62118	5/8	2.02	0.0729		
62119	5/8	2.02	0.0729		
Average:		2.02	0.0730	0.328	0.27

The specific gravity data show a high degree of consistency within each size, suggesting considerable uniformity of composition. While there is a trend toward increasing density with diameter, the variation is negligible except for the smallest size.

Comparison of the calculated weights per foot with the manufacturer's rated values (Table 14) shows large differences except in the smallest size. In the other three sizes the rated values are all low, by as much as 20 percent.

5.5 Summary

The densities of all of the materials tested varied from 0.061 to 0.075 lb/in^3. However, there was almost as much variation between sizes and specimens of individual materials. Thus, there does not appear to be any justification for choosing among the materials on the basis of density. Rather, a nominal density of about 0.07 lb/in^3 would appear to be a reasonable value to use in design considerations involving any of the materials.

No significant, consistent variation of density with diameter was observed for any of the materials.

The nominal diameter of Material G, which approximates the diameter of the bare rope, was found to be a poor index of the cross sectional area of this material.

The actual weights of Materials G and N, in most sizes, were found to be significantly greater than the rated values reported by their respective manufacturers.

6. TENSILE STRENGTH

In order to investigate the variation of tensile strength with diameter for the rod and rope materials, it is necessary to use end fittings which are capable of generating the true tensile strengths of these materials. Although significant progress has been made in the development of such end fittings, the state of the art has not yet progressed to the point where the true tensile strengths of all of the materials can be developed consistently.

Tensile tests were performed on various sizes of the materials. Except where otherwise specified, the test conditions were the same as those used previously to evaluate commercial end fittings.

6.1 Material A

Tests were performed on four sizes of single-strand Material A using Type R/P fittings. The specimens were each 18 to 20 in long with a gripped length of 2 in at each end. The test results are given in Table 15. The first two tests listed were performed at a constant loading rate of 125 lbf/min. All of the other tests were performed at a constant crosshead speed of 0.2 in/min. The maximum tensile stresses were calculated on the basis of the nominal diameters which, as pointed out earlier, are close to the actual diameters for this material.

All but three of the tests were terminated by the specimen pulling out of the end fitting, intact. The three specimens which fractured were the only ones which attained the manufacturer's rated breaking loads. The maximum stresses in these three cases were in the vicinity of 290000 lbf/in^2.

Better results were obtained in an earlier investigation using aluminum block end fittings [10]. In that work, two specimens of 0.0865-in Material A were fractured in the free length at an average breaking load of 1820 lbf, which corresponds to a tensile strength of 308000 lbf/in^2.

As mentioned earlier, 7-strand Material A rope is composed of seven 0.119-in strands. The highest breaking load ever achieved in this laboratory with 7-strand Material A is 20200 lbf [10]. This specimen was tested with aluminum block end fittings and failed by crushing in the fittings. The calculated maximum stress for this case is 259000 lbf/in .

6.2 Material E

Only 1/2-in diameter specimens of Material E were tested in this investigation. Of these, only one failed in the free length (Test No. 71183, Table 10). The maximum load attained, 32850 lbf, is believed to be indicative of the true strength of this material and corresponds to a maximum stress of 168000 lbf/in^2.

Several tests of Material E in the 13/16-in diameter size were performed in an earlier study [10]. None of these specimens failed in the free length but the highest maximum load attained was 45850 lbf. This exceeds the manufacturer's rated breaking load, 35000 lbf, but corresponds to a maximum tensile stress of only 88000 lbf/in^2.

6.3 Material G

A series of tests were performed on three sizes of Material G. Following one of the manufacturer's recommendations, these tests were

Table 15 - Tensile Tests of Material A (Single Strand)
End fitting: Type R/P

Test No.	Nominal diameter	Potting compound	Rated load	Maximum load	Maximum stress	Failure
	in		lbf	lbf	lbf/in^2	
82252	0.031	C2W3	220	106	141000	(a)
82253	0.043	C2W3	440	363	250000	(a)
92274	0.043	C1W1	440	365	252000	(a)
92275	0.063	C1W1	800	560	178000	(a)
92276	0.063	C1W1	800	210	67000	(a)
92277	0.084	C1W1	1500	1590	287000	(b)
92278	0.084	C1W1	1500	1000	181000	(a)
102326	0.119	C2W3	3000	3300	297000	(b)
102327	0.119	C2W3	3000	3210	288000	(b)

(a) Pullout.

(b) Fracture adjacent to fitting.

carried out with Type R/P end fittings and GS potting compound. All of the specimens failed strandwise at the fitting at comparatively low loads. These data are not reported here.

Better results were obtained with Mod 4 end fittings and C2W3 potting compound. See Table 16. The specimens were 48 in or more in length and were tested at a crosshead speed of 0.2 in/min.

All of the 5/16-in diameter specimens failed in the free length. The maximum loads are thus believed to be indicative of the true strength of the material and come within four percent of the manufacturer's rated breaking load.

Two of the three 7/16-in diameter specimens also failed in the free length. The third specimen failed strandwise in the end fitting at a comparable load level. The maximum loads exceed the manufacturer's rated breaking load for this size and compare favorably with the results of other tests which were believed to have approached the true tensile strength of 7/16-in Material G. (See Table 3.)

The first 5/8-in specimen tested also failed in the free length with a maximum load close to the manufacturer's rated breaking load. The second 5/8-in specimen pulled out of the end fitting at a comparatively low load.

The maximum tensile stresses listed in Table 16 were calculated on the basis of the nominal diameter. Considering the specimens which failed in the free length it appears that, on a stress basis, the 5/8-in size has considerably lower strength than the other two sizes. However, it was shown from density measurements that the nominal diameter of Material G is not, in fact, a good index of the actual cross sectional area of this material. A better parameter to use in comparing the strengths of different sizes is the strength/weight ratio. This is demonstrated in Table 16 which shows that, for those specimens which failed in the free length, the strength/weight ratio is a more consistent indicator of strength, for various sizes, than is stress. The strength/weight ratio shows no correlation with density (Table 12) and no consistent variation with diameter. For all of the specimens which failed in the free length the strength/weight ratio is 140000 lbf-ft/lb, within 10 percent.

Tests conducted elsewhere on 3/16-in Material G showed a somewhat higher strength/weight ratio [13]. However, it is apparent that these

Table 16 - Tensile Tests of Material G
End fitting: Mod 4
Potting compound: C2W3

Test No.	Nominal diameter	Rated load	Maximum load	Maximum stress(a)	Strength/ weight(b)	Failure
	in	lbf	lbf	lbf/in^2	lbf-ft/lb	
92268	5/16	10000	9980	130000	136000	(c)
92269	5/16	10000	9650	126000	132000	(c)
92270	5/16	10000	9940	129000	136000	(c)
71190	7/16	17500	19800	132000	141000	(c)
81239	7/16	17500	20250	135000	145000	(d)
92271	7/16	17500	21200	141000	151000	(c)
92272	5/8	32000	31100	101000	128000	(c)
92273	5/8	32000	21700	71000	89000	(e)

(a)Based on nominal rope diameter.

(b)Maximum load divided by actual weight per foot from Table 13.

(c)Failure in free length.

(d)Strandwise in end fitting.

(e)Pullout.

ratios were calculated using the rated, rather than actual, weight of Material G.

6.4 Material N

In the evaluation of commercial end fittings it was found (Table 7) that all of the fittings tested perform equally well with Material N. Accordingly, the Type R/V fitting, which is the easiest to use, was initially selected for this study of the effects of size on the tensile strength of this material. All of the specimens failed by pinching off at the end fitting although the manufacturer's rated breaking loads were attained in several instances. These data are not reported here.

The test series was repeated using Mod 4 fittings and C2W3 potting compound, and somewhat better results were obtained. These results are given in Table 17. The free length of all of the specimens was 16 in or more. Test Nos. 91262, 81240 and 81241 were performed at a crosshead speed of 0.75 in/min. The other tests were performed in a different testing machine at 0.2 in/min. The maximum stresses were calculated on the basis of the nominal diameters, which approximate the actual diameters of the rods minus the coatings.

All but one of the specimens failed by pulling out of the Mod 4 fitting. The exception, in Test No. 92265, failed in the free length. This specimen exhibited the highest maximum stress, 154000 lbf/in^2, and failed at a load within three percent of the manufacturer's rated breaking load. One specimen in each of the other sizes exceeded the rated breaking load although free length failures were not obtained.

The Mod 4 fitting used for the test of the 5/8-in specimen was specially designed with a thicker wall to avoid the possibility of a failure in the fitting.

Table 17 - Tensile Tests of Material N
End fitting: Mod 4
Potting compound: C2W3

Test No.	Nominal diameter	Rated load	Maximum load	Maximum stress	Failure
	in	lbf	lbf	lbf/in^2	
92264	1/4	7800	3000	61000	(a)
92265	1/4	7800	7550	154000	(b)
91262	3/8	12000	13100	119000	(a)
92266	3/8	12000	9800	89000	(a)
81240	1/2	20000	23700	121000	(a)
81241	1/2	20000	17850	91000	(a)
91263	1/2	20000	18900	96000	(a)
92267	5/8	30000	38000	124000	(a)

[a] Pullout.

[b] Failure in the free length.

6.5 Summary

The various end fittings which were used in this study were generally inadequate to generate the true tensile strengths of the rod and rope materials. There were several exceptions, however, notably with Material G, in which failures in the free lengths of the specimens were obtained. In all of these cases the measured breaking loads of the materials were close to, or in excess of, the manufacturers' rated loads. In several cases where free length failures were not obtained the maximum loads nevertheless exceeded the rated values. It appears, therefore, that while some of the end fittings used are capable of generating the rated loads of the rod and rope materials, the full potential of these materials is not being realized. There is an indicated need for evaluation of other types of commercial end fittings and for further development of improved fittings.

The limited data available do not show any consistent variation of true tensile strength with either density or diameter. Thus, it appears that the maximum stress for failure in the free length does not depend on size for Materials A, E and N. Unfortunately, stress is not a useful parameter for Material G since the cross sectional area of this material cannot be calculated accurately from the nominal diameter. For this material the strength/weight ratio is a more consistent and meaningful parameter than the maximum stress. Similarly, strength comparisons of Material G with other materials should be made on the basis of the strength/weight ratio rather than the maximum stress or the breaking load for a given nominal diameter. Note, however, that these considerations apply to the true tensile strengths of the rod and rope materials, not to the actual breaking loads achieved with commercial end fittings. The breaking stresses of these materials with commercial end fittings do, in fact, tend to increase as the diameter of the rod or rope is reduced. Thus, for example, the rated breaking load for two parallel rods or ropes of 1/4-in diameter is greater than that of a single 3/8-in member, although the combined weight or cross sectional area of the former is less.

Although the true tensile strengths of the specimen materials could not be obtained consistently, the data show quite conclusively that Material A is significantly stronger than Materials E, G and N. This is in agreement with the manufacturers' rated breaking strengths and results, no doubt, from the fact that Material A is reinforced with S-glass while the other materials use E-glass reinforcement.

7. MODULUS OF ELASTICITY

A series of tests was performed to determine the tensile moduli of elasticity of the rod and rope materials. These tests were performed in

a universal testing machine at a crosshead speed of 0.2 in/min. The strain measuring system was calibrated against a micrometer-screw extensometer calibrator having a resolution of 10 microinches.

The selection of end fittings for these tests was not critical since the specimens did not have to be loaded to failure. The tests were, in fact, discontinued prior to failure. The load-strain curves were linear in every case. The results are given in Table 18. The moduli of elasticity were calculated, from the slopes of the curves, on the basis of the nominal diameters of the specimen materials. As pointed out earlier, for single-strand Material A and for Material E the nominal diameter is close to the actual diameter. For Materials G and N the nominal diameter approximates the average diameter of the unjacketed rope and the uncoated rod, respectively.

The results show that for Materials A and N the modulus of elasticity does not vary in any consistent manner with diameter and, in fact, there were variations in modulus even within a given size and material. This observation is consistent with earlier findings [10] and would suggest that the compositions of these materials are not uniform even within a single size. However, the density measurements reported earlier tend to refute this. For these two materials all of the measured modulus values exceed the rated values reported by the manufacturers (7.0×10^6 lbf/in^2 for Material A, 6.34×10^6 lbf/in^2 for Material N).

On the basis of the measurements made, a nominal modulus of 7.5×10^6 lbf/in^2 would appear to be a reasonably typical value for design purposes involving Materials A, E and N.

The moduli of elasticity for Material G, as listed in the table, are obviously inaccurate since they were calculated on the basis of the nominal diameters which, it has been shown, do not provide good estimates of the actual cross sectional areas. If the listed moduli are corrected by multiplying them by the ratio of calculated weight to actual weight, the values in Table 19 are obtained. It is seen that, although there is a trend toward lower moduli as diameter increases, the variation is comparatively small. However, each of the modulus values is significantly less than the manufacturer's rated value, 6.0×10^6 lbf/in^2.

Several tests were performed to determine the moduli of uncoated 1/2-in Material N rod and unjacketed 7/16-in Material G rope. The results show that the coating and the jacket contribute little to the stiffness of the products in tension.

Table 18 - Tensile Modulus of Elasticity

Test No.	Material	Nominal diameter	Modulus of elasticity[a]
		in	lbf/in^2
92292	A	0.043	7.7×10^6
92293	A	0.063	7.1
92294	A	0.063	7.4
92295	A	0.084	7.9
92296	A	0.084	7.3
102328	A	0.119	7.8
102329	A	0.119	7.8
92297	E	1/2	7.4
92285	G	5/16	5.2
92286	G	5/16	5.0
92287	G	7/16	4.7
92288	G	7/16	4.7
92290	G	5/8	3.9
92291	G	5/8	3.6
92279	N	1/4	8.6
101321	N	3/8	8.5
92282	N	1/2	6.9
92283	N	1/2	7.4
92284	N	5/8	8.2

[a]Calculated on the basis of the nominal diameter.

Table 19 - Corrected Modulus of Elasticity of Material G

Test No.	Nominal diameter	Modulus of elasticity Uncorrected[a]	Modulus of elasticity Corrected[b]
	in	lbf/in^2	lbf/in^2
92285	5/16	5.2×10^6	5.2×10^6
92286	5/16	5.0	5.0
92287	7/16	4.7	4.6
92288	7/16	4.7	4.6
92290	5/8	3.9	4.7
92291	5/8	3.6	4.3

[a]From Table 18.

[b]Multiplied by ratio of calculated to actual weights of jacketed rope, Table 13.

8. LOW-TEMPERATURE FLEXIBILITY

Three-point bending tests were performed on Materials E, G and N in order to evaluate their flexural moduli of elasticity at low temperatures. The specimens were simply supported on 2-in diameter metal rods, over fixed spans, and loaded transversely at the center through another 2-in diameter rod. The test fixtures were completely enclosed in a low-temperature test chamber which was mounted between the crossheads of a universal testing machine. The test temperature was achieved with a fan which circulated air over a supply of dry ice and the specimen. Thermocouples were used to measure temperature during the initial exploratory experiments but a low-temperature thermometer was found to be adequate for the tests. The specimens were exposed to the test temperature for about one hour prior to loading. Load was then applied at a crosshead speed of about 1 in/min and an extension rod was used to transfer the center displacements of the specimens to the outside of the chamber where they were measured with a dial gage.

8.1 Material E

Low-temperature flexibility tests were performed on specimens of 1/2-in Material E which were 25 in long and supported on a 20-in span. The load-deflection curves were linear up to high levels, after which the slopes decreased slightly. From elementary strength-of-materials considerations, the flexural modulus E_f was calculated from the slope S of the linear portion of each curve using the expression

$$E_f = \frac{4L^3}{3\pi} \frac{S}{D^4} = 54320\ S$$

where D is the nominal diameter of the rod and L is the span. The results are given in Table 20.

These results show that the flexural modulus of elasticity is essentially unaffected by temperature down to −81 °F. It is also seen that the flexural modulus is larger than the tensile modulus of elasticity, which was found to be 7.4×10^6 lbf/in^2 for Material E (Table 18). This implies that the modulus of elasticity for Material E is substantially greater in compression than in tension.

All of the tests were discontinued without failure of the specimens since the test setup limited the permissible deflections. It is of interest to compare the maximum strains reached in the bending tests with those obtained in tension tests. Assuming linear elastic behavior it can be shown that the maximum strain corresponding to a deflection of 3.9 in is 0.029. The actual maximum strain, due to the nonlinear

Table 20 - Low-Temperature Flexibility of Material E

Test No.	Temperature	Flexural modulus	Maximum deflection[a]
	°F	lbf/in²	in
95298	77	8.2×10^6	3.87
95299	77	8.2	3.96
95300	77	8.5	3.81
95301	-20	8.4	3.93
95302	-38	8.3	3.84
95303	-58	8.3	3.80
95304	-63	8.5	3.78
35008	-65	8.3	3.96
95305	-74	8.3	3.90
95306	-81	8.6	2.37

[a] Tests discontinued without failure.

Table 21 - Low-Temperature Flexibility of Material N

Test No.	Temperature	Flexural modulus	Maximum deflection[a]
	°F	lbf/in²	in
95307	77	7.4×10^6	3.51
95308	77	7.4	3.51
95309	77	7.5	3.65
95310	-40	7.6	2.87
35007	-60	7.4	2.96
35006	-67	7.8	2.56[b]
95311	-76	7.8	2.97

[a] Deflection at failure, except as noted.

[b] Test discontinued prior to failure.

behavior, was undoubtedly larger than this. The tensile strain corresponding to the true tensile strength of Material E (Test No. 71183, Table 10) is only 0.023. It thus appears that this material is capable of withstanding larger strains in bending than in tension.

8.2 Material G

Bending tests of 7/16-in Material G proved to be difficult to accomplish due to the extreme flexibility of this material. It was necessary to reduce the span to 4.75 in in order to increase the required loads to values which were significantly larger than the weight of the specimen itself.

Three tests were performed at temperatures down to −67 °F. The load-deflection curves were nonlinear right from the start due to slippage in the rope construction. No meaningful values of the flexural modulus could be obtained, but a comparison of the load-deflection curves for the three tests showed that the flexibility was unaffected by the temperature.

8.3 Material N

Three-point bending tests on 1/2-in Material N were performed in the same manner as those described for Material E. With the exception of one test which was terminated prematurely, all of the tests culminated in failure due to crushing of the matrix material on either the tensile or compressive sides of the rod specimens. The results of the tests are given in Table 21.

The flexural modulus of elasticity at room temperature is seen to be within the range of values obtained for the tensile modulus (Table 18). All of these values exceed the manufacturer's rated flexural modulus, 6.39×10^6 lbf/in^2. The results also show an insignificant increase in the flexural modulus as temperature is reduced to −76 °F.

Assuming linear elastic behavior, it can be shown that the maximum bending strain for a deflection of 3.5 in is 0.026. The actual maximum bending strain at room temperature was undoubtedly larger than this due to the observed nonlinearity in the load-deflection curves at large deflections. The maximum tensile strain for this material (Test No. 92265, Table 17) is only 0.022. Thus, in keeping with the findings for Material E, this material is also capable of withstanding larger strains in bending than in tension.

The manufacturer of Material N reports a flexural strength of 125000 lbf/in^2. If this stress is divided by the rated flexural modulus, a maximum bending strain of 0.0196 is obtained, which is

substantially less than the values obtained at room temperature in the present tests.

8.4 Summary

The flexibility of Materials E, G and N is essentially unaffected by temperature down to about -70 °F. However, the rope product, Material G, is far more flexible than either of the rod products due to normal slippage in the rope construction under bending deformations.

The load-deflection relationships for the two rod products are linear elastic up to large deflections. The strain at fracture for both of these materials is greater in bending than in tension. However, with Material N the bending strain at fracture is substantially less at -40 °F than it is at room temperature.

The flexural modulus of elasticity of Material E is noticeably greater in bending than in tension.

For Material N the flexural modulus of elasticity and the bending strain at fracture both exceed the manufacturer's rated values at room temperature.

9. VIBRATION EFFECTS

Simulated Aeolian vibration tests were performed on 7/16-in Material G rope and 1/2-in Material N rod. In these tests the specimen was pretensioned to a predetermined load level, allowed to relax under load for 24 h, and then vibrated transversely while the original load level was maintained essentially constant. The transverse vibration was excited with an electrodynamic shaker which was mechanically coupled to the specimen immediately adjacent to the first nodal point. The shaker was tuned to the resonant frequency of the specimen. The maximum double amplitude of vibration of the specimen was measured with a filar microscope. All of the tests were performed under the ambient laboratory conditions of temperature and humidity.

The first tests were carried out in an apparatus in which the tensile loads are applied by dead weights through a 10:1 lever system. The tensile load capacity of this apparatus is 5500 lbf and the required specimen length is 18 ft. When it was found that failures of the specimen materials could not be obtained with this arrangement a larger facility was assembled. The new facility employs a screw-powered testing machine to apply the tensile loads and a more powerful electrodynamic shaker for larger amplitudes of vibration. Specimen length for this facility is 23 ft.

The test results are given in Table 22. GRP guy-lines in field installations have been reported to vibrate at frequencies within the range used in these tests, but the amplitudes of vibration observed in the field are apparently smaller than those used in these tests. It should be noted that, for a given amplitude of vibration, considerably more power was required for Material G than for Material N. This implies that Material G, due its rope construction, has a greater damping capacity than Material N rod.

The results show that two end fitting failures were obtained with Material G specimens. In neither case did this cause failure of the rope itself. Two specimens of Material N failed at the point where the shaker was attached to the rod. These failures were due to fretting and would not have occurred under actual wind-induced vibration. One Material N rod failed at 16000 lbf before the transverse vibration was applied.

In no case did a rod or rope specimen fail under conditions which could be attributed to the Aeolian vibration itself. It appears, therefore, that Aeolian vibration is not a matter of serious concern with these materials, at least under conditions comparable to those used for the tests. It has been suggested, however, that when a long guy-line is assembled from two different materials in series, with a heavy connector, then Aeolian vibration can induce a whipping action with substantially greater amplitudes than those examined here.

The test results also give some indication of the long-term strengths of the specimen materials under ambient conditions. It appears that 7/16-in Material G can sustain 9000 lbf for extended periods, while 16000 lbf may be an upper limit for 1/2-in Material N with Type R/V fittings.

10. STRESS-RUPTURE STRENGTH

Sustained load tests, in tension, were carried out on Materials G and N in order to study the long-term strengths of these materials under severe environments. The tests were performed at elevated temperatures, both with and without high humidity conditions.

The specimens were mounted such that the central portion of the rod or rope material passed concentrically through a cylindrical temperature-humidity test chamber while the ends remained exposed to the ambient laboratory environment. The specimens were sufficiently long so that the end fittings were unaffected by the temperature and humidity in the chamber.

Table 22 - Simulated Aeolian Vibration Tests

Test No.	Specimen material	End fitting	Tensile load	Frequency	Double amplitude	Duration	Failure
			lbf	Hz	in	cy	
34005	G	R/P	1000	62	0.4	1.0×10^8	(a)
44054	G	R/P	3500	62	0.4	$200. \times 10^8$	(a, b)
54083	G	F/A	4500	63	0.4	0.55×10^8	(a)
54084	G(f)	F/A	5500	65	0.4	0.54×10^8	(a)
54085	G	F/A	9000	-	-	-	(c)
84257	G	Mod 4	9000	48	1.0	0.80×10^8	(a)
54081	N	R/P	3500	57	0.4	0.51×10^8	(a)
54082	N	R/P	4500	65	0.6	0.50×10^8	(a)
64143	N	P	10000	67	1.5	0.01×10^8	(d)
64144	N	P	10000	67	1.5	0.58×10^8	(a)
74215	N	R/V	14000	54	1.5	1.26×10^8	(a)
64145	N(g)	P	15000	81	1.5	2.14×10^8	(d)
74216	N	R/V	16000	-	-	-	(e)
74214	N	R/P	16000	50	1.5	1.25×10^8	(a)

(a) Test discontinued without failure of specimen.

(b) Bail of Type R/P fitting failed at 0.50×10^8 cycles and was replaced.

(c) Reused Type F/A fitting failed immediately upon application of transverse vibration.

(d) Failure in specimen at point of attachment to shaker.

(e) Failure in specimen before application of transverse vibration.

(f) Same specimen as in Test No. 54083.

(g) Same specimen as in Test No. 64144.

With a specimen in place, the chamber was heated to the desired test temperature in about 45 min. For tests conducted under high humidity conditions, the humidity in the chamber was also raised to the desired level during this interval. The specimen remained under these conditions for two to three hours prior to testing. The test loads were then applied and thereafter maintained constant until failure resulted or the test was terminated.

10.1 Material G

Stress-rupture tests of 7/16-in Material G were performed at 200 °F, under both ambient and high humidity conditions. In addition, one test was accomplished at room temperature. Two types of end fittings were used; Type R/P with C1W1 potting compound and Mod 4 with C2W3 potting compound. Several failures were obtained at the Type R/P fittings; none at the Mod 4 fittings.

Table 23 presents the results of those tests which resulted in failure of the specimen within the chamber or which were discontinued without failure. The tests which resulted in failure at the end fitting will be discussed later.

The short-time tensile strength of 7/16-in Material G at room temperature is approximately 20500 lbf (Table 16). Table 23 shows that with a load of only 16000 lbf failure occurs in less than a half hour at room temperature. Raising the temperature to 200 °F causes further reductions in the load-carrying capability of this material. The short-time tensile strength at 200 °F is only 13700 lbf and the long-term strength is less than 9000 lbf. The diminution of strength with time under load has also been observed at room temperature for Material G [13].

Although elevated temperature severely degrades the strength of Material G, humidity appears to have little effect. This is, perhaps, attributable to the polyurethane jacket on Material G, which remained intact even after failure of the rope strands. In fact, the test results at 200 °F, both with and without high humidity, appear to be part of a single statistical population, as shown in Figure 17. The "best-fit" straight line drawn through the plotted points was determined by the method of least squares.

10.2 Type R/P Fittings on Material G

As mentioned above, two types of end fittings were used for the long-term tests of 7/16-in Material G: Type R/P with C1W1 potting compound, and Mod 4 with C2W3 potting compound. No failures were obtained at the Mod 4 fittings. The results of those tests which culminated in failure at the Type R/P fittings are given in Table 24. Also included

Table 23 - Stress-Rupture of 7/16-in Material G

Test No.	Temperature	Humidity	Load	Rupture time
	°F	pct rh	lbf	h
83255	77	45-50	16000	0.45
53070	200	<25	13700	0.00
53073	200	<25	12000	0.35
53078	200	<25	9500	0.6
53079	200	<25	9000	17.3
53080	200	<25	8500	>140.[a]
83256	200	>95	13125	0.00
103325	200	>95	11000	0.1
103324	200	>95	10000	3.4
103322	200	>95	9000	27.1

[a]Test discontinued prior to failure.

Table 24 - Stress Rupture of Type R/P End Fittings
with 7/16-in Material G
Potting compound: C1W1

Test No.	Load	Rupture time
	lbf	h
53071	13000	0.1
72313	13000	0.2
53072	12500	1.5
53074	11000	0.05
53075	10500	6.5
53076	10000	1.1
53077	9500	8.[a]
83254	9000	12.[a]
53080	8500	>140.[b]

[a]±7 h, exact time not determined.

[b]Test discontinued prior to failure.

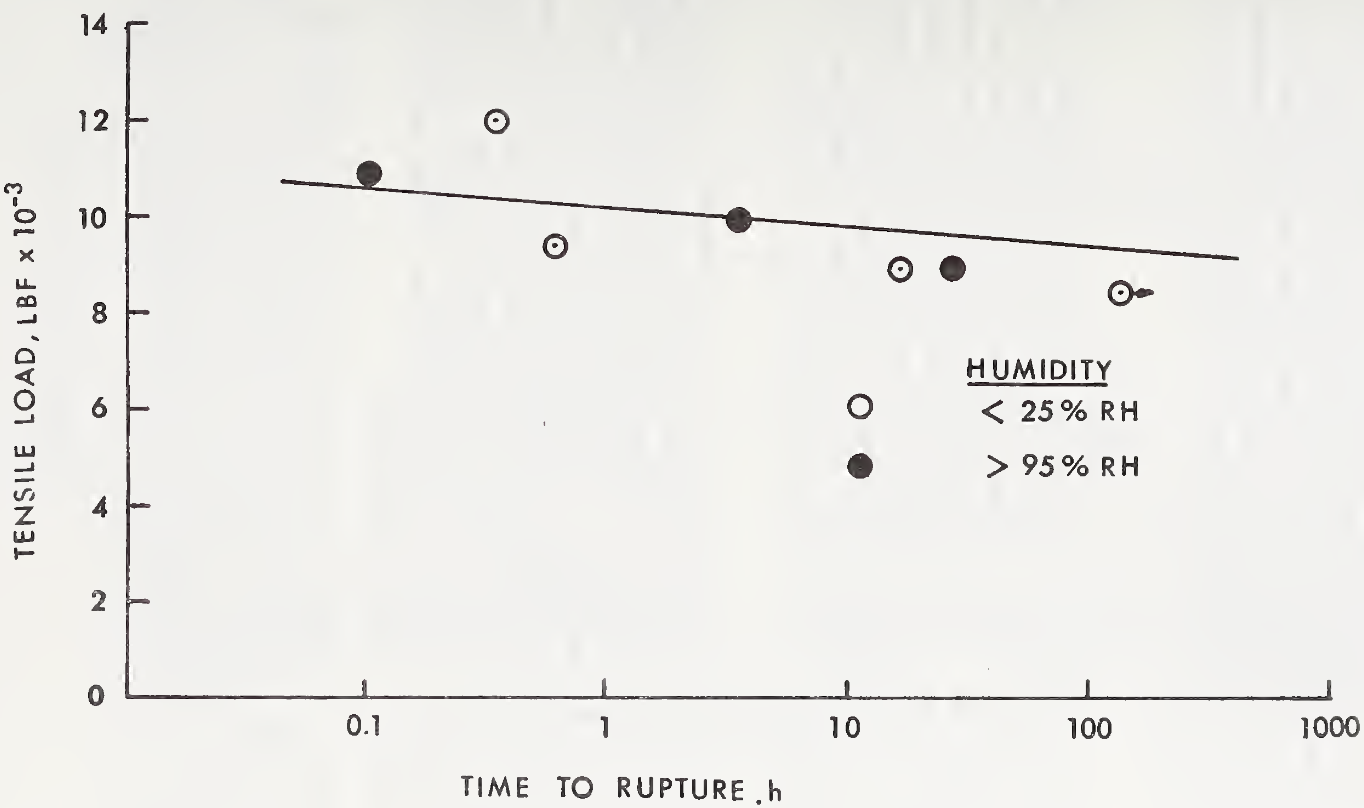


Figure 17 - Stress-rupture properties of 7/16-in Material G at 200°F.

is one test which was discontinued prior to failure. Temperature and humidity data are not given in the table since the fittings were all exposed to the ambient laboratory atmosphere, approximately 77 °F and 45 to 50 percent relative humidity.

The results are plotted in Figure 18 with the "best-fit" straight line. These data may be compared with the short-time tensile strength of the Type R/P fittings with C1W1 potting compound on 7/16-in Material G, which was found to be approximately 13600 lbf (Table 6). Comparison of Figures 17 and 18 shows that for short times the strength of the fitting at room temperature exceeds that of Material G at 200 °F, but the trend of the data suggest that for long times the reverse is true. It is clear that this combination of end fitting, potting compound and rope material is not conducive to long-term strength even under ambient temperature and humidity conditions.

10.3 Material N

Stress-rupture tests of 1/2-in Material N were performed at 150, 175 and 200 °F both with and without high humidity conditions. Type R/V end fittings were used. Most of the specimens failed in the test chamber, some failed at the end fitting, and some tests were discontinued prior to failure. In addition, three specimens which were tested at 150 °F failed in the free length just outside of the test chamber. The temperature and humidity conditions at the point of failure in these specimens are not known accurately but are obviously less than 150 °F (the test temperature) and less than 45 percent rh (the ambient humidity), respectively.

Table 25 presents the results of all tests except those which resulted in failure at the end fittings. These results are plotted in Figure 19, which shows that the stress-rupture properties of Material N are unusual in several respects. The stress-rupture strength of this material appears to be essentially unaffected by temperature and humidity in a range of temperatures extending from some point below 150 °F up to at least 200 °F. (This, of course, explains why failures in the free length just outside of the test chamber were apt to occur.) It is clear that the lower limit of this temperature range does not extend down to room temperature since, as Table 22 shows, this material can sustain higher loads at room temperature.

The "best-fit" straight line is seen to be nearly horizontal. Examination of the figure suggests that a straight line may not actually represent the data properly; except for one anomalous point at 16000 lbf and 48.4 h the data suggest a stress-rupture curve which is asymptotic to the horizontal at about 14000 lbf. It thus appears that the stress-rupture behavior of 1/2-in Material N is characterized by a threshold load above which the time to rupture is relatively short. Loads below

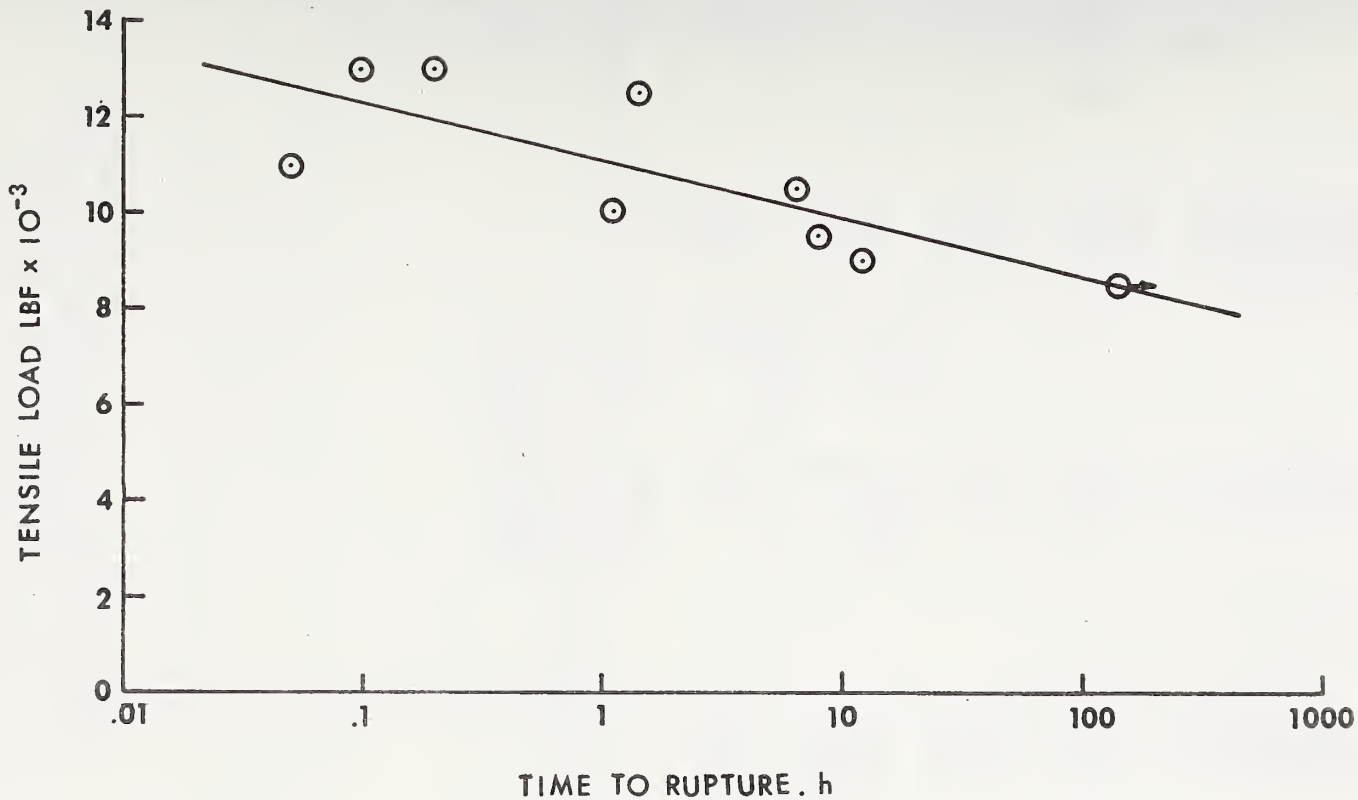


Figure 18 - Stress-rupture properties of Type R/P end fittings on 7/16-in Material G. C1W1 potting compound.

Table 25 - Stress Rupture of 1/2-in Material N

Test No.	Temperature °F	Humidity pct rh	Load lbf	Rupture time h
63125	200	<25	16000	48.4
63126	200	<25	15500	0.05
63127	200	<25	15250	0.1
63129	200	<25	15000	0.05
63128	200	<25	15000	0.2
63130	200	<25	14000	6.7
63131	200	<25	14000	>286.[a]
63134	175	<25	14250	>115.[a]
63135	175	<25	14000	>112.[a]
63136	175	<25	13000	>111.[a]
63137	150	<25	15000	0.3
63139	150	<25	14500	144.6
63142	150	<25	14125	32.05
63138	<150	<45	14750	0.1
63140	<150	<45	14250	1.2
63141	<150	<45	14250	5.1
73208	200	>95	14250	68.5
73209	200	>95	14125	99.5
73210	175	>95	14250	0.4

[a] Test discontinued prior to failure.

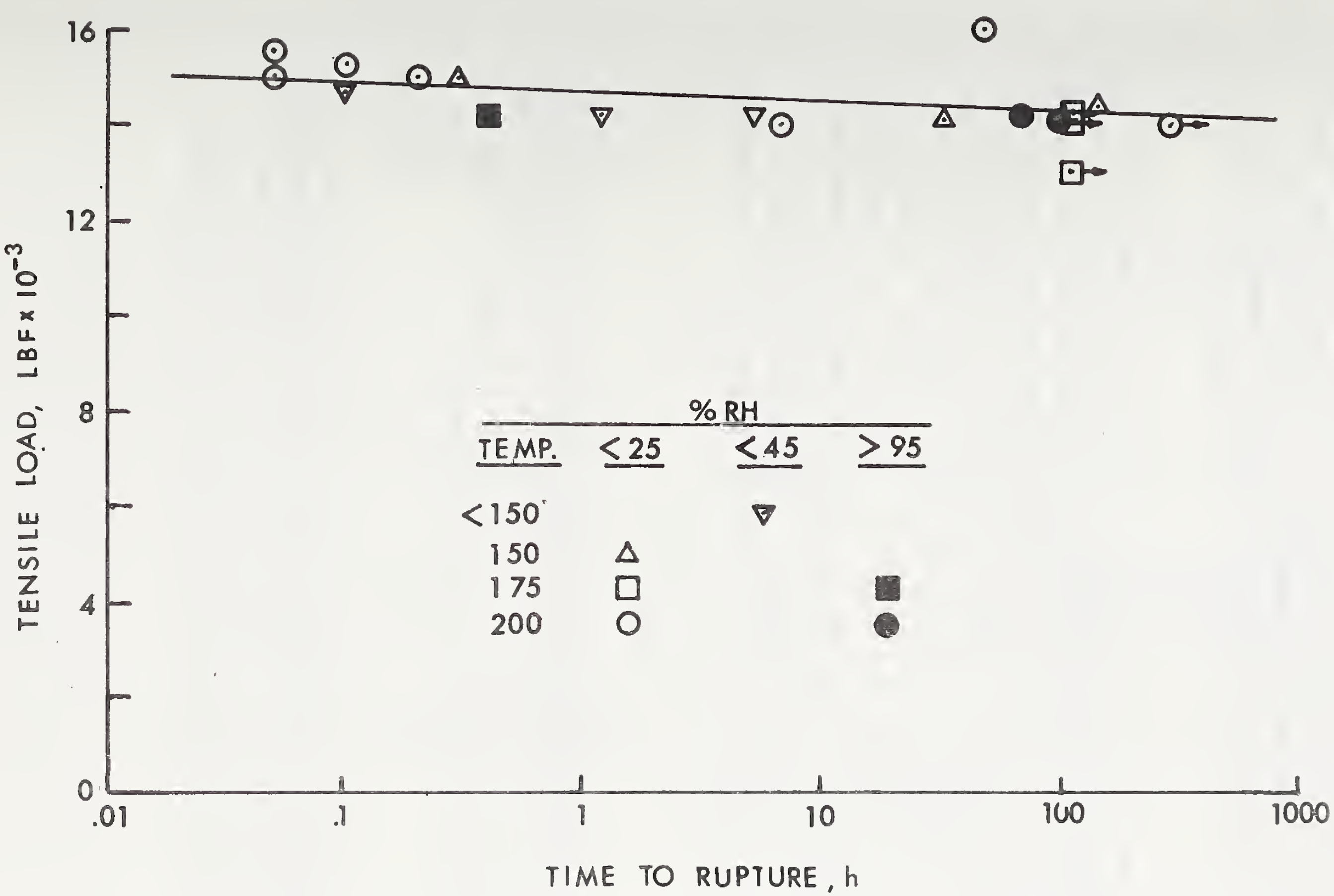


Figure 19 - Stress-rupture properties of 1/2-in Material N.

the threshold can be sustained for longer periods. The threshold load, 14000 lbf, corresponds to a tensile stress of about 70000 lbf/in^2 and is 70 percent of the manufacturer's rated load.

10.4 Type R/V Fittings on Material N

Table 26 presents the results of those stress-rupture tests of Material N which culminated in failure at the Type R/V end fitting. Also included in the table are those tests which were discontinued prior to failure. Temperature and humidity data are not given because the fittings were exposed to the ambient laboratory atmosphere. These results may be compared with the short-time breaking strength of Type R/V fittings on 1/2-in Material N, which is approximately 20600 lbf (Table 4).

The stress-rupture data are plotted in Figure 20. A meaningful straight line which characterizes these data cannot be obtained in this case since all but one of the failure points are bunched into less than one time decade. In this situation the least-squares method is unduly influenced by the single point at 16000 lbf and 0.1 h. Nevertheless, the general trend of the data is clear; it is similar to Figure 19 in that it indicates a threshold at about 14000 lbf. Since the Type R/V fitting is a metallic, mechanical fitting its strength is virtually time-independent in the temperature range of interest. Its long-term strength when gripping Material N rod is determined by the properties of the rod which, as pointed out, are lower at 150 °F than at room temperature. It may be concluded that the performance of Type R/V fittings on Material N would be less than adequate for long-term service at moderately elevated temperatures.

10.5 Material A

Stress-rupture tests of single-strand Material A, which were conducted elsewhere [14], show that the load-carrying capability of this material, like Material G, decreases continuously with time under load. Furthermore, these data also indicate no detrimental effect of high humidity on the long-term strength at room temperature.

10.6 Summary

The long-term strength of Material N is somewhat less at 150 °F than at room temperature. In the range 150 to 200 °F the stress-rupture properties are characterized by a threshold at about 70000 lbf/in^2; stresses above this value tend to produce failure in relatively short times while below this threshold the rupture time can be substantial.

Table 26 - Stress Rupture of Type R/V End Fittings with 1/2-in Material N

Test No.	Load	Rupture time
	lbf	h
74216	16000	0.1
63133	14500	2.85
73207	14500	5.65
63132	14500	19.6
63134	14250	>115.[a]
73211	14125	9.8
73212	14125	16.5
63135	14000	>112.[a]
63136	13000	>111.[a]

[a] Test discontinued prior to failure.

Table 27 - Effects of Storage on Tensile Breaking Loads of Material A (7-strand)
Coil diameter: 2.5 ft, unsupported
End fitting: Type F
Gripped length: 24 in, each end

Test No.	Storage temperature	Free length	Maximum load[a]
	°F	in	lbf
56086	125	24	15800
56087	150	24	15600
56088	175	22	15400
56089	200	24	15000

[a] All specimens failed strandwise at the end fitting.

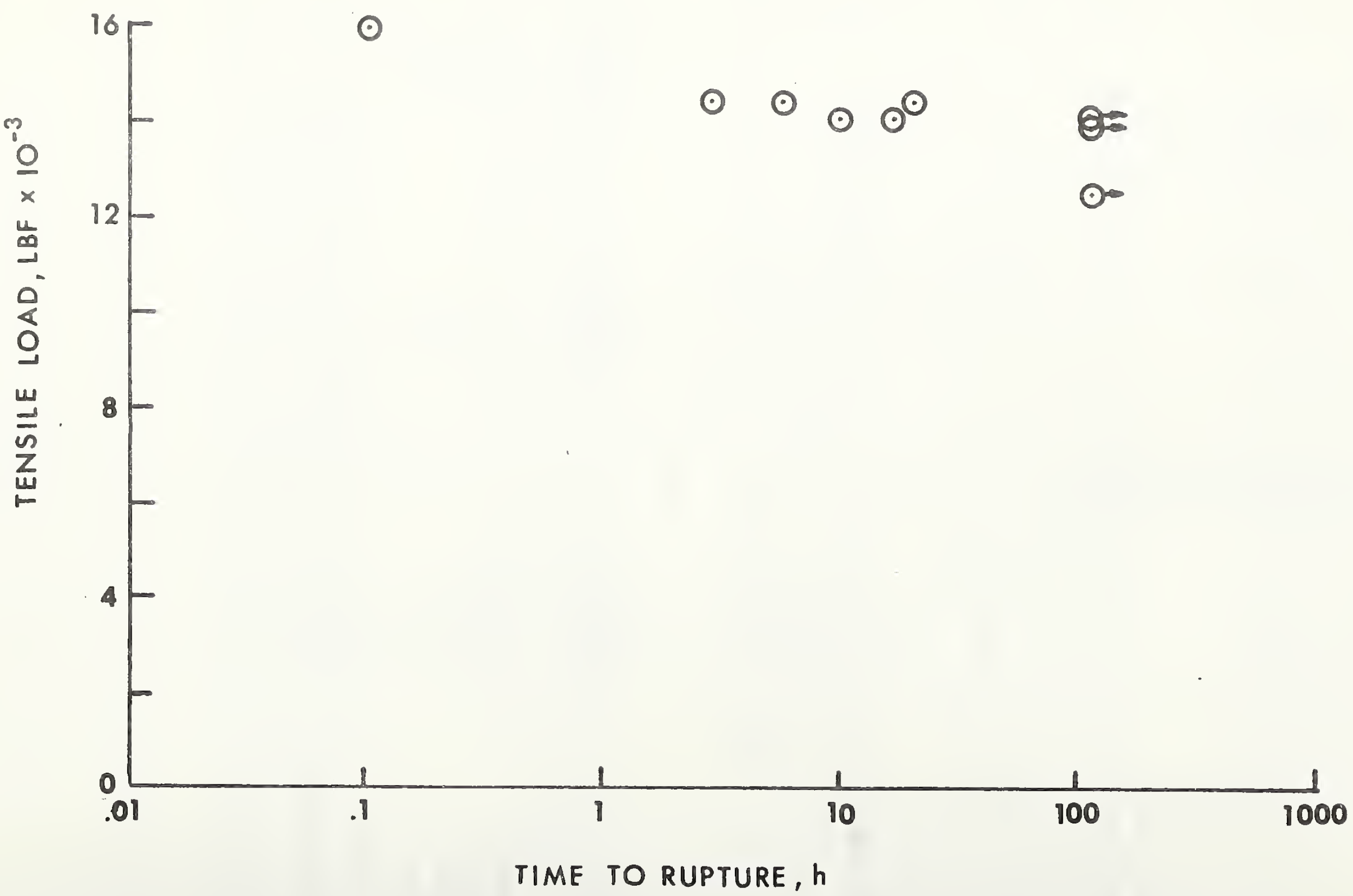


Figure 20 - Stress-rupture properties of Type R/V end fittings on 1/2-in Material N.

The long-term strength of Material G is considerably less at 200 °F than at room temperature. The load-carrying capabilities of Material G and Material A decrease continuously with time under load.

Quite surprisingly, there is no evidence of a detrimental effect of high humidity on the stress-rupture strengths of these materials. It is possible that such an effect, if it exists, manifests itself only after long times.

11. LONG-TERM STORAGE

One of the principal advantages of the rope products over the rod products is their flexibility, which permits them to be coiled to relatively small coil diameters for convenience in shipment and storage. In sizes up to about 5/8-in diameter the rod products may also be coiled, albeit to relatively large coil diameters. It has occasionally been observed, however, that coiled rods exhibit a tendency to buckle under moderate elevated temperatures such as might be encountered in certain storage situations.

The buckling failures are quite localized. See Figure 21. The mechanism by which they form is not fully understood. The glass fibers near the inside surface of the coil apparently buckle radially inward and fracture. This process is undoubtedly facilitated by the reduced stiffness of the matrix material at the elevated temperature.

A series of tests was conducted to examine the combinations of coil diameter and temperature at which buckling failures occur. For this purpose a large, walk-in type, elevated-temperature test chamber was designed and constructed to accomodate coils up to 10 ft in diameter, which is about the largest practical shipping size. The chamber is 12 x 12 x 8 ft high and is fabricated from aluminum honeycomb sandwich panels with a window for visual inspection of the specimens during test. The temperature in the chamber can be raised to 200 °F in one hour. Heat is supplied by a distributed bank of small radiant heaters having a combined capacity of 11 kW. Power to each heater is adjustable with a variable autotransformer and the temperature is maintained by a temperature controller. An electric fan provides continuous air circulation for better temperature uniformity.

Each specimen consisted of three full turns of the rod or rope material with the ends fastened to prevent uncoiling. Most of the specimens were unsupported, that is, coiled without a drum, but several were coiled inside or outside a sheet metal drum. The coils were suspended, by fine wires, from the ceiling of the chamber is order to permit free air circulation around them. Four thermocouples, mounted at 90° intervals around each coil, were used to monitor temperature. The

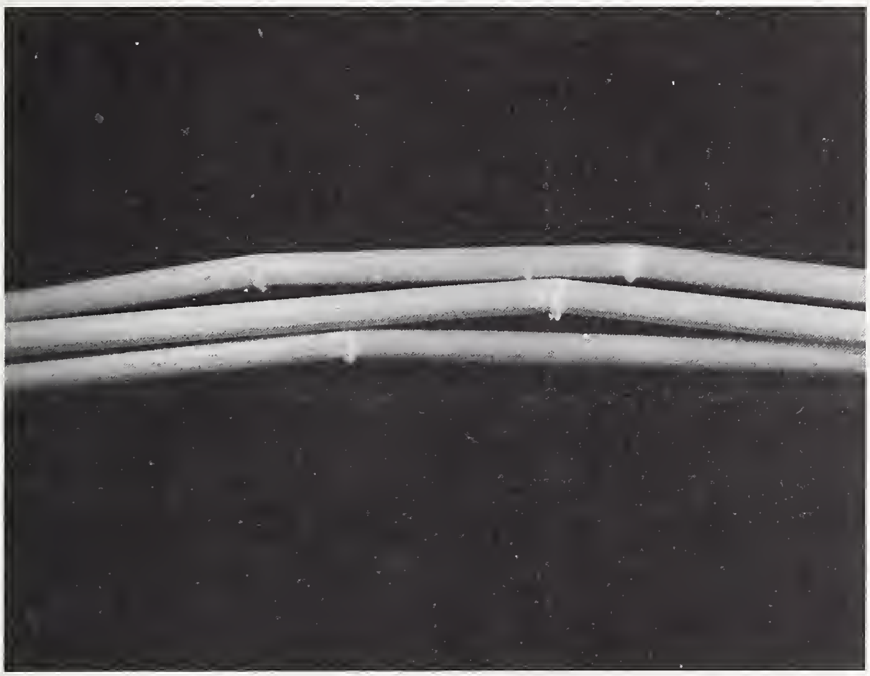


Figure 21 - Typical buckles in 1/2-in Material E, resulting from coiled storage at elevated temperature.

temperature distribution on each coil was uniform within 5 °F at each test temperature.

Tests were performed at 125, 150, 175 and 200 °F. The duration of each test was 30 days (720 h). Following each test the specimens were uncoiled, examined for permanent set, and cut into convenient lengths for tensile testing. The tensile test conditions were the same as those described earlier.

11.1 Material A

Material A in the 7-strand configuration was coiled to a diameter of 2.5 ft and subjected to storage tests at 125, 150, 175 and 200 °F. The maximum elastic bending stress and strain due to coiling are approximately 31000 lbf/in^2 and 0.0040, respectively. No buckles were observed after 720 h at each test temperature.

After the storage tests the coils were unwound. There was no evidence of any significant amount of permanent set in the material as a result of the storage testing. A length of material was cut from each coil and tested in tension. The results of these tests are given in Table 27. All of the specimens failed strandwise at the end fitting. By comparison with the results given in Table 2 it is seen that the storage conditions had essentially no effect on the breaking load of the material.

11.2 Material E

Storage tests of 1/2-in Material E were performed on 7- and 10-ft diameter coils. The maximum elastic bending stresses and strains due to coiling are approximately 50000 lbf/in^2 and 0.0060, respectively, for the 7-ft coil and 35000 lbf/in^2 and 0.0042, respectively, for the 10-ft coil. Tests were conducted on unsupported coils, on coils wrapped inside a drum, and on coils wrapped outside a drum. The approximate times to buckling are given in Table 28. The table shows that at 125 °F both coil sizes survived the 720-h test without buckling. The 7-ft coils tested at 150 °F all buckled within three days. There is some evidence that the support offered by a drum delays buckling, and that wrapping outside a drum is preferable to wrapping inside a drum. A 10-ft unsupported coil buckled at 175 °F. Supported coils of 10-ft diameter, which were intended for test at 200 °F, buckled at 180 °F during heat-up to the test temperature.

The storage specimens were uncoiled after the storage tests. No appreciable amount of permanent set was evident in the material from coils which had not buckled. Material which had buckled was permanently bent in the vicinity of the buckles.

Table 28 - Storage Tests of 1/2-in Material E

Test No.	Coil diameter	Coil support[a]	Storage temperature	Approximate time to buckling
	ft		°F	h
36010	7	U	125	>720.
36011	10	U	125	>720.
36016	7	U	150	0.5
46058	7	ID	150	24.
46058A	7	OD	150	72.
36017	10	U	150	>720.
36022	10	U	175	0.25
66147	10	ID	180[b]	0.0
66148	10	OD	180[b]	0.0

[a] U = unsupported; ID = wrapped inside drum; OD = wrapped outside drum.

[b] Buckled at 180 °F during heat-up to 200 °F.

The material was cut into lengths convenient for tensile testing. The tensile breaking loads of fifteen specimens which contained buckles were between 3800 and 12000 lbf, depending upon the severity of the buckles. All of the tensile failures initiated at buckles.

The results of tensile tests on specimens which did not contain buckles are given in Table 29. The first specimen listed was cut from a 7-ft coil which had been stored at 125 °F and had not buckled. The other specimens were cut from 7-ft coils which had been stored at 150 °F and which had buckled, although the tensile specimens themselves did not contain buckles.

The two specimens which were tested with Type R/V fittings failed by splitting inside the fitting. This is a different mode of failure than had been obtained on Material E which had not been stored at elevated temperature. In those tests the specimens failed by pinching off at the fitting. The maximum loads, however, are essentially the same (see Table 4).

The specimens which were tested with Type R/P fittings exhibited two different modes of failure. In two of the tests failure was by pullout. In the other tests failure was by pinching off the specimen just inside the fitting. The maximum loads are not directly comparable with those obtained previously with virgin Material E (Table 6) since different potting compounds were used. On the basis of the different failure mode obtained with the Type R/V fittings and the low load achieved in Test No. 76229, it appears that some degradation of the strength of Material E may have resulted from the elevated temperature exposure.

11.3 Material G

Storage tests of 1.5-ft diameter coils of 7/16-in Material G were performed at 125, 150, 175 and 200 °F. All of the coils were unsupported and all sustained the 720-h tests without buckling or permanent set.

Tensile tests were performed on specimens which had been cut from these coils after the storage tests. The tests were conducted with Type R/P fittings and C1W1 potting compound. All of the specimens failed by pinching off just inside the fitting. The results of the tests are given in Table 30. These results may be compared with those from tests on Material G which had not been stored at elevated temperature (Table 6). This comparison shows that the elevated temperature storage appears to have produced a small improvement in the breaking loads, which is probably attributable to a beneficial postcuring effect of the elevated temperature exposure.

Table 29 - Effects of Storage on Tensile Breaking Loads of Unbuckled 1/2-in Material E
Coil diameter: 7 ft
Free length of tensile specimens: 21 in.

Test No.	Storage temperature	Coil support[a]	End fitting	Potting compound	Maximum load	Failure
	°F				lbf	
56097	125	U	R/V	-	19200	(b)
56098	150	U	R/V	-	19400	(b)
66158	150	ID	R/P	C1W1	17300	(c)
61159	150	ID	R/P	C1W1	22200	(d)
76229	150	ID	R/P	C1W1	13000	(d)
76230	150	ID	R/P	C1W1	24300	(c)
76231	150	ID	R/P	C1W1	17500	(c)
76232	150	ID	R/P	C1W1	20700	(c)
66156	150	OD	R/P	C1W1	18200	(c)
66157	150	OD	R/P	C1W1	17950	(c)

[a] U = unsupported; ID = wrapped inside drum; OD = wrapped outside drum.

[b] Longitudinal splitting in fitting.

[c] Pinching off.

[d] Pullout.

Table 30 - Effects of Storage on Tensile Breaking Loads of 7/16-in Material G
Coil diameter: 1.5 ft, unsupported
End fitting: Type R/P
Potting compound: C1W1
Gripped length: 7 in, each end

Test No.	Storage temperature	Free length	Maximum load[a]
	°F	in	lbf
56093	125	20	16400
56094	150	20	15600
56095	175	21	16400
56096	200	20	14800

[a] Failure by pinching off at the end fitting.

Table 31 - Storage Tests of 1/2-in Material N

Test No.	Coil diameter	Coil support[a]	Storage temperature	Approximate time to buckling
	ft		°F	h
36013	7	U	125	>720.
36014	10	U	125	>720.
36019	7	U	150	>720.
46059	7	ID	150	>720.
46059A	7	OD	150	>720.
36020	10	U	150	>720.
36024	7	U	175	0.75
76220	7	ID	175	24.
76221	7	OD	175	>720.
36025	10	U	175	>720.
46056	10	U	200	>720.
76218	10	ID	200	>720.
76219	10	OD	200	>720.

[a] U = unsupported; ID = wrapped inside drum; OD = wrapped outside drum.

11.4 Material N

Storage tests of 1/2-in Material N were performed on 7- and 10-ft diameter coils. The maximum elastic bending stresses and strains due to coiling were approximately 44000 lbf/in^2 and 0.0060, respectively, for the 7-ft coil, and 31000 lbf/in^2 and 0.0042, respectively, for the 10-ft coil. The results of the storage tests are given in Table 31. It was found that a 7-ft unsupported coil buckled at 175 °F and that the time to buckling was delayed by wrapping inside a drum. When wrapped outside a drum no buckling occurred during the 720-h duration of the tests. The 10-ft coils did not buckle at temperatures up to 200 °F.

After the storage tests the specimens were uncoiled and an interesting phenomenon was observed. While the coils which had been exposed in the unsupported condition did not exhibit any appreciable permanent set, those coils which had been wrapped inside or outside of a drum tended to remain in a circular configuration with radii of curvature between 20 and 26 ft. The reason for this phenomenon is not known.

Tensile specimens of Material N were cut from the coils. The free lengths of all of the specimens were 20 in or more. None of the specimens contained buckles. The results of tensile tests on these specimens are given in Table 32.

A variety of failure modes was observed. In the tests of specimens which had been exposed to 150 °F, the lowest maximum loads were obtained on specimens which failed by longitudinal splitting inside the Type R/P fitting. Because of the curvature in the specimens it appeared that the splitting was induced, to some extent, by the tendency for the specimens to straighten under the tensile loads. However, an attempt to correlate the splitting failures with the radii of curvature of the specimens was unsuccessful.

A splitting failure was also observed in the specimen which had been exposed to 175 °F and which had been tested with Type R/V fittings. Virgin Material N which had been tested with Type R/V fittings had not failed this way (Table 4). On the basis of this observation plus similar ones with Material E it is concluded that the elevated temperature exposure produces some subtle change in the rod materials which increases their susceptibility to splitting failures.

The maximum loads obtained with Type R/V and Type F fittings are only slightly less than those obtained with virgin material (Tables 4 and 2, respectively).

Table 32 - Effects of Storage on Tensile Breaking Loads of Unbuckled 1/2-in Material N

Test No.	Storage temperature °F	Coil diameter ft	Coil support[a]	End fitting	Potting compound	Maximum load lbf	Failure
66162	150	7	ID	R/P	C1W1	19250	(b)
66163	150	7	ID	R/P	C1W1	14700	(c)
76236	150	7	ID	R/P	C1W1	21000	(b)
76237	150	7	ID	R/P	C1W1	20600	(d)
66160	150	7	OD	R/P	C1W1	17500	(c)
66161	150	7	OD	R/P	C1W1	16500	(c)
76233	150	7	OD	R/P	C1W1	20500	(b)
76234	150	7	OD	R/P	C1W1	20000	(b)
76235	150	7	OD	R/P	C1W1	15700	(c)
56103	175	7	U	R/V	-	19500	(c)
56099	175	10	U	R/P	Note (e)	21600	(b)
56101	175	10	U	F	-	18800	(c)
56104	200	10	U	R/V	-	18500	(b)
56100	200	10	U	R/P	Note (e)	20400	(b)
56102	200	10	U	F	-	18700	(c)

(a) U= unsupported; ID = wrapped inside drum; OD = wrapped outside drum.

(b) Pinching off.

(c) Longitudinal splitting in fitting.

(d) Pullout.

(e) C2W3 in narrow half of potting head, balance C1W1.

11.5 Summary

The rope products, Materials A and G, showed no tendency to buckle due to long-term exposure to elevated temperatures in a coiled condition. A 2.5-ft diameter coil of 7-strand Material A and a 1.5-ft diameter coil of 7/16-in Material G survived 30 days at 200 °F without evidence of buckling, permanent set, or reduction in breaking strength.

The rod products, Materials E and N, were both susceptible to buckling when exposed to elevated temperatures in a coiled condition. Tests on 1/2-in diameter rod showed that with a coil-diameter/rod-diameter ratio of 168, Material E buckled at 150 °F and Material N buckled at 175 °F. With a diameter ratio of 240, Material E buckled at 175 °F while Material N survived 30 days at 200 °F without buckling. The stress and strain levels were only a fraction of those imposed in the tension, bending and stress-rupture tests.

Buckling, when it occurred, invariably took place within the first 72 h of elevated-temperature exposure. Rods which did not buckle within 3 days also survived the entire 30-day exposures.

The support provided by wrapping coils on a drum delays or resists buckling compared with unsupported coils. Coils wrapped outside a drum are more resistant to buckling than those wrapped inside a drum. However, with Material N, exposure to elevated temperatures while wrapped on a drum caused some permanent set to develop in the material.

The tensile strength of buckled material is severely reduced. However, there are indications that the breaking strength of material apart from the buckles is only slightly impaired.

12. CONCLUSIONS

An extensive and varied test program was carried out on four, commercially available, GRP rod and rope materials. Materials A and G are rope products, Materials E and N are rod products. The results of these tests warrant the following conclusions:

1. A nominal density of 0.07 lb/in^3 is a reasonable value for use in design considerations involving these materials, regardless of diameter. The actual weights of Materials G and N were found to be significantly greater than the rated values reported by their respective manufacturers.

2. Material A, which is fabricated with S-glass, is significantly stronger than the other three materials, which use E-glass reinforcement. The true tensile strengths of

Materials A, E and N do not appear to vary with diameter. Since the cross-sectional area of Material G cannot be calculated from the nominal diameter, the strength/weight ratio is a more consistent and meaningful parameter for this material than tensile strength.

3. A tensile modulus of elasticity of 7.5 x 10^6 lbf/in^2 is a reasonably typical value for design purposes involving Materials A, E and N, regardless of diameter. This exceeds the manufacturers' rated values. The modulus of Material G, appropriately corrected for the cross sectional area, is approximately 5 x 10^6 lbf/in^2.

4. The flexibility of Materials E, G and N is essentially unaffected by temperature down to about -70 °F. However, the rope product, Material G, is far more flexible than the rod products. The strain at fracture for the rod products is greater in bending than in tension but, for Material N, the bending strain at fracture is substantially less at -40 °F than at room temperature.

5. Aeolian vibration does not appear to be a serious problem in GRP guy lines, at least under conditions similar to those which were simulated in the laboratory. This conclusion may not apply to guy lines which, because of their design, are subject to whipping action. Material G, due to its rope construction, has a greater damping capacity than Material N.

6. The stress-rupture strength of Material N, in the range 150 to 200 °F, is characterized by a threshold at about 70000 lbf/in^2. Stresses above this value tend to produce failure in relatively short times while below this threshold the rupture time is comparatively long. By contrast, the load-carrying capabilities of Materials A and G decrease continuously with time under load. There is no evidence of a detrimental effect of high humidity on the stress-rupture strength of these materials. If such an effect does exist it becomes apparent only after long exposures.

7. The rod products are susceptible to buckling when exposed to elevated temperatures in a coiled condition involving relatively low bending stresses. The resistance to buckling is increased by wrapping the coils on a drum but this tends to produce some

permanent set in Material N. Diameter-temperature relationships for avoiding buckling were established. The rope materials are not susceptible to buckling. The tensile breaking strengths of the materials are not seriously degraded by the coiled exposures except where buckling has occurred.

The performance of the GRP materials was evaluated with five, commercially available end fittings. These include three dead-end types (P, F and F/A), a mechanical compression type (R/V), and a potted compression type (R/P). It was found that:

1. Not all of the fittings are suitable for all of the GRP materials but, with judicious selection, the manufacturers' rated breaking loads of the GRP materials can be approached with the commercial fittings. With only one combination (Type F/A fitting on Material G), however, could the true tensile strength of the GRP material be attained.

2. Although the true tensile strengths of the materials show no appreciable variation with diameter the actual breaking stresses, with commercial end fittings, tend to increase as diameter is reduced.

3. The performance of the Type R/P fitting is strongly dependent on the potting compound which is used.

4. Certain of the commercial end fittings were found to be inadequate either for conditions involving Aeolian vibration or for long-term service at moderately elevated temperatures.

A new, experimental, shear-type potted end fitting was developed. This fitting, the NBS Mod 4, is capable of attaining the true tensile strengths of Materials E and G, and is at least as good as the commercial fittings on Material N. No failures of the Mod 4 fitting were experienced in simulated Aeolian vibration tests or in stress-rupture tests.

*   *   *

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APPENDIX

Factors for converting U.S. customary units to the International System of Units (SI) may be found in ASTM Standard Metric Practice Guide (ASTM Designation E380-70). Copies are available from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103. Conversion factors for units used in this paper are given in the following table:

Quantity	U.S. customary unit	SI unit	Conversion factor
Force	pound-force (lbf)	newton (N)	1 lbf = 4.448 N
Length	foot (ft)	meter (m)	1 ft = 0.3048 m
	inch (in)	meter (m)	1 in = 0.0254 m
Mass (weight)	pound (lb)	gram (g)	1 lb = 453.6 g
	pound (lb)	kilogram (kg)	1 lb = 0.4536 kg
Temperature	degrees Fahrenheit (°F)	degrees Celsius (°C)	°C = (5/9) (°F - 32)
Density[(a)]	lb/in^3	kg/m^3	1 $lb/in^3 = 2.768 \times 10^4$ kg/m^3
Loading rate	lbf/min	N/s	1 lbf/min = 0.07413 N/s
Speed	in/min	m/s	1 in/min = 4.233×10^{-4} m/s
Strength/weight[(b)]	lbf-ft/lb	N·m/kg	1 lbf-ft/lb = 2.989 N·m/kg
Stress	lbf/in^2	N/m^2	1 lbf/in^2 = 6895 N/m^2
Weight per foot[(c)]	lb/ft	kg/m	1 lb/ft = 1.488 kg/m

(a) Density in g/cm^3 is numerically equal to specific gravity.

(b) Defined in Table 16.

(c) Defined on page 28.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

An extensive and varied test program was carried out on four GRP rod and rope materials to evaluate tensile strengths, moduli of elasticity, flexibility at low temperatures, effects of simulated Aeolian vibration, and stress-rupture properties at moderate elevated temperatures both with and without high humidity. The effects of elevated temperature on long-term storage capabilities were investigated, and diameter-temperature relationships were established for avoiding buckling due to storage in a coiled condition.

The performances of five commercially available end fittings on these materials were examined in terms of the breaking loads attained in tensile tests. Using finite-element analyses, an improved end fitting was developed which is capable of approaching the true tensile strengths of two of the GRP materials. An experimental stress analysis of the improved fitting was performed.

17. KEY WORDS

Aeolian vibration, simulated; composite materials; end fittings for GRP rod and rope; grips, guy; guys, antenna; humidity, effects on GRP; mechanical properties of GRP; pultruded rod; reinforced plastics, rod and rope; rope, GRP; static fatigue of GRP.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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